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APR 30 1998

DOE-0732-98

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Dear Mr. Saric and Mr. Schneider:

TRANSMITTAL OF REVISED RADIATION TRACKING SYSTEM APPLICABILITY STUDY

The purpose of this letter is to transmit, for your review and approval, the revised "Radiation Tracking System (RTRAK) Applicability Study." This revision of the RTRAK Applicability Study incorporates information contained in Revision 0 issued July 1997, as well as information contained in an addendum issued September 1997 entitled, "RTRAK Applicability Measurements in Locations of Elevated Radionuclide Concentrations."

Additionally, this report contains an extension of the RTRAK calibration equations to allow the RTRAK to be used with confidence in high activity areas, as well as a discussion of the effects of gamma photon interferences on calibration and data quality. Finally, this report incorporates responses to the U.S. Environmental Protection Agency (U.S. EPA) and Ohio Environmental Protection Agency (OEPA) comments on the July 1997 RTRAK Applicability Study.

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If you have any questions or concerns regarding this document, please contact Robert Janke at (513) 648-3124.

Sincerely,

Johnny Reising

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FERNALD ENVIRONMENTAL MANAGEMENT PROJECT
FERNALD, OHIO

RTRAK APPLICABILITY STUDY

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ONLY

MAY 1998

U.S. DEPARTMENT OF ENERGY
FERNALD AREA OFFICE

(20701-RP-0003)
REVISION 1

1430

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LIST OF ACRONYMS AND ABBREVIATIONS

ALARA	as low as reasonably achievable
COC	constituent of concern
cps	counts per second
DGPS	differential global positioning system
DOE	US Department of Energy
FEMP	Fernald Environmental Management Project
FWHM	full width half maximum
GPS	global positioning system
HPGe	high purity germanium detector
IRDP	integrated remedial design package
keV	kiloelectrovolt
MCA	multichannel analyzer
MDC	minimum detectable concentration
mph	miles per hour
NaI	sodium iodide
NIST	National Institute of Standards and Technology
pCi/g	picocuries per gram
PHA	pulse height analysis
PMT	photomultiplier tube
ppm	parts per million
PSP	project specific plan
PVC	polyvinylchloride
QA/QC	quality assurance/quality control
RI/FS	remedial investigation/feasibility study
ROI	region of interest
RTRAK	Radiation Tracking System
sec	second
SEP	Sitewide Excavation Plan

USID	Uranium in Soils Identification Demonstration
WAC	waste acceptance criteria

EXECUTIVE SUMMARY

This report sets the stage for the routine utilization of a field-deployable analytical technique for use in soil remediation: the Radiation Tracking System (RTRAK), a mobile (tractor-mounted) sodium iodide (NaI) detector-based system for measuring gamma rays emitted by radionuclides of concern in soil. The overall objective of this report is to evaluate and document RTRAK characteristics and RTRAK data quality parameters. This report, Revision 1 of the RTRAK Applicability Study, incorporates information contained in Revision 0 of the same study that was issued in July 1997, as well as information contained in an addendum to Revision 0 (issued in September 1997, entitled "RTRAK Applicability Measurements in Locations of Elevated Radionuclide Concentrations"). Additionally, this report contains an extension of the RTRAK calibration equations to allow RTRAK to be used with confidence in high activity areas, as well as a discussion of the effects of gamma photon interferences on calibration and data quality. Finally, this report incorporates responses to US EPA and OEPA comments on Revision 0 of the July 1997 RTRAK report, and the September 1997 addendum.

A series of studies were conducted in order to evaluate optimum RTRAK operating conditions and the quality of data generated by the RTRAK. Three key data quality elements were examined: precision, minimum detectable concentration (MDC), and accuracy. These studies were conducted in areas of both low and high radionuclide activity concentrations. As a result of these studies, the preferred RTRAK operating conditions are a 4-second data acquisition time with a travel speed of 1.0 mph. These operating conditions offer the best compromise between acceptable analytical data quality and practical field implementation.

Measurements taken using the RTRAK and a high-purity germanium (HPGe) detector in the same locations exhibit good agreement between total uranium, thorium-232 and radium-226 concentrations measured by RTRAK and concentrations of the same isotopes measured by HPGe. This is the case for both static (not moving) and dynamic (moving) measurements. Large standard deviations (poor precision) for individual RTRAK measurements preclude the use of individual measurements to quantify uranium at any concentration levels from Final Remediation Level (FRL) to Waste Acceptance

Criteria (WAC). Two consecutive measurements collected with a 4-second acquisition time must be averaged for the precision to be acceptable at WAC levels while 18 measurements must be aggregated to yield meaningful data at an FRL of 82 ppm. Similarly, two measurements of thorium-232 and six measurements of radium-226 must be averaged to give meaningful data at concentrations near their respective FRLs of 1.5 and 1.7 pCi/g.

For individual measurements with a four second data acquisition time, the MDC of radium-226 is 130% of the FRL of 1.7 pCi/g, and the MDC of thorium-232 is 93% of the FRL of 1.5 pCi/g. The individual measurement MDC for total uranium (57 pCi/g; 216 ppm) substantially exceeds the FRL of 82 ppm, even for a four-second data acquisition time. Because MDCs are dependent upon the standard deviations of the data, and because standard deviations are dependent upon the number of measurements aggregated, aggregating measurements provide an effective way of lowering the MDCs.

Thus, to improve precision and lower the MDC, RTRAK data must be spatially averaged over an area larger than the area for the individual measurements. The issue with spatial averages is how large an averaging area is required to reduce measurement error and MDCs to acceptable levels without sacrificing required spatial resolution. For example, data from precision studies show that averaging individual RTRAK measurements with a data acquisition time of two seconds over a circular area with a radius of ten feet is approximately equivalent to increasing data acquisition time to eight seconds. If RTRAK data are collected with an eight second acquisition time, increasing the averaging area from a circle with a radius of ten feet to one of 20 feet would be equivalent to increasing the acquisition time to 32 seconds.

A new calibration study extended the calibration range by about a factor of three for total uranium and by about a factor of ten for radium-226 (higher concentrations of thorium-232 were not encountered in the new calibration locations). The agreement between the new and the old calibrations is good over the full range of concentrations evaluated for thorium-232 and radium-226. For uranium-238, the agreement between the two calibrations is poorer at low concentrations, apparently reflecting the low reliability of low-concentration measurements. At concentrations above 60 ppm, the extended range calibration yields lower values than the original calibration. However, the extended range calibration does a better job of accommodating and adjusting for interferences.

Because the new calibration included much higher radionuclide concentrations than were used in the old calibration, interference effects had to be addressed. Spectrum interferences increase as the concentrations of thorium-232 and radium-226 increase. All three analytes of interest (uranium-238, thorium-232, and radium-226) are subject to interferences from one or more of the other analytes. Uranium-238 is the most severely affected. In areas where thorium-232 or radium-226 are of the order of tens of pCi/g, the uranium-238 results are questionable and spectra need to be carefully examined to determine whether the interferences preclude their use. Radium-226 results may also be affected when thorium-232 is in the range of 30 pCi/g and again spectra must be examined to determine the impact of the interferences. At high radium-226 concentrations, thorium-232 may be biased low; data are not yet available to quantify the level at which these latter interferences become significant.

Specific RTRAK user guidelines, data interpretation guidelines, and measurement strategies and approaches are addressed in the "User's Manual" (DOE 1998a). The reader should consult this document for specifics of how the RTRAK will be used in the soil remediation process.

Section 1

SECTION 1.0
INTRODUCTION, RTRAK DESCRIPTION, REPORT SCOPE AND OBJECTIVES

1.1 INTRODUCTION

The Fernald Environmental Management Project (FEMP) is currently conducting remediation of site soils that are radiologically and chemically contaminated. Soil contamination originated from airborne dispersion of both fugitive and stack emissions throughout the production period (1952-1989), as well as from direct releases due to spills and site disposal practices. While a number of chemicals and radionuclides contribute to site risk, contaminated soil volume, and areal extent of contamination, only five species contribute large cumulative percentages of contamination. These five species, the "primary contaminants of concern" (COCs), include total uranium, thorium-232, thorium-228, radium-226 and radium-228. Because thorium-228 and radium-228 have been shown to be in secular equilibrium with thorium-232 (letter from J. Craig to J. Saric and T. Schneider, 1997), only total uranium, radium-226, and thorium-232 are of analytical concern.

A number of applications makes the use of field-deployable screening instruments attractive for detecting activities of these three COCs of interest in a "real time" mode, as opposed to traditional sampling and laboratory analysis protocols. These include:

- Complete coverage of areas to assess the spatial patterns of contaminant distribution in pre-design investigations;
- Rapid identification of areas potentially exceeding Waste Acceptance Criteria (WAC) during soil excavation activities;
- Complete coverage and rapid identification of areas potentially exceeding final remediation levels (FRLs), hot spot criteria, and WAC exceedances in pre-certification activities;
- Rapid attainment of data that allows HPGe measurements or physical samples to be focused on specific areas; and
- Support of the process for achieving as low as reasonably achievable (ALARA) goals in soil remediation.

This report sets the stage for the routine utilization of a field-deployable analytical technique in soil remediation: a mobile sodium iodide (NaI) detector-based system (mounted on a John Deere tractor) for measuring gamma rays. This instrument platform, known as the Radiation Tracking System (RTRAK), is briefly described below.

1.2 BRIEF DESCRIPTION OF RTRAK SYSTEM

The RTRAK system is a gamma-ray measurement system mounted on a tractor. The measurement system consists of a 4x4x16 inch NaI detector and associated electronics that provide high-speed pulse height analysis. This system allows the collection of a gamma ray energy spectrum, which can be analyzed to identify and quantify radioactive isotopes that may be present within the detector's viewing area. The tractor is also equipped with a global positioning system (GPS), operated in a real-time differential mode to provide location coordinates. Each energy spectrum is tagged with the location coordinates provided by the GPS. All energy and location data are stored on magnetic media by an on-board computer system. This information is used to accurately locate and subsequently map radiological data within the measurement area.

The detector is positioned on the tractor horizontal to the ground and perpendicular to the direction of travel at a height of approximately 31 cm above the ground. The normal operation of the RTRAK consists of driving the tractor over the measurement area at a predetermined speed. Spectra are continuously collected at regular intervals, typically a few seconds. The viewing area size is a function of the tractor speed, the acquisition time, and the detector's geometrical configuration. For example, for the 4x4x16 inch detector at the 31 cm height, the viewing area is 8.8 m^2 for a single measurement when the tractor is moving at one mile per hour, with a 4-second data acquisition time (typical operating parameters). Table 1-1 gives RTRAK single measurement fields of view as a function of speed and data acquisition time. Figure 1-1 depicts how the field of view is determined (a 1.2 meter radius for the RTRAK stationary field of view is the basis for determining the moving RTRAK field of view).

The RTRAK collects data which are used to generate a gamma photon energy spectrum. This spectrum may be processed to generate total activity or radionuclide-specific activities. In the total activity mode, all of the counts in the spectrum are totaled and used to identify elevated activity areas; there is no radionuclide-specific information. Alternatively, the system can be used to generate qualitative and quantitative results for uranium-238, radium-226, and thorium-232. These results are based on gamma rays emitted by the radionuclides or members of their respective decay chains. A more detailed description of the RTRAK, the characterization and calibration of its NaI detectors, and how gamma photons are measured and quantified is provided in Appendix A.

1.3 PREVIOUS STUDIES

In 1997, a series of method validation studies pertaining to in-situ gamma spectrometry were issued. These studies addressed analytical aspects of in-situ gamma spectrometry such as precision, accuracy, detection limits, robustness, comparability with laboratory analytical data, and data quality levels. One report and three addenda concerned HPGe detectors, and one report; Revision 0 of this report and one addendum dealt with the RTRAK. These reports and addenda are:

- Comparability of In-Situ Gamma Spectrometry and Laboratory Data, 1997
- Comparability of Total Uranium Data as Measured by In-Situ Gamma Spectrometry and Four Laboratory Methods, September 1997 (Addendum #1)
- Comparability of In-Situ Gamma Spectrometry and Laboratory Measurements of Radium-226, October 1997 (Addendum #2)
- Effect of Environmental Variables upon In-Situ Gamma Spectrometry Data, December 1997 (Addendum #3)
- RTRAK Applicability Study, Revision 0, July 1997
- RTRAK Applicability Measurements in Locations of Elevated Radionuclide Concentrations, September 1997 (Addendum #1)

The July 1997 "Comparability of In-Situ Gamma Spectrometry and Laboratory Data" (DOE 1997a) is referred to in this study as the HPGe Comparability Study. The July 1997 "RTRAK Applicability Study" is referenced in this document as DOE 1997b.

1.4 SCOPE OF THE REPORT

This report combines the July 1997 "RTRAK Applicability Study" (DOE 1997b) and the September 1997 Addendum #1 to the RTRAK Applicability Study. Further, this report extends the calibration range of the RTRAK using data from higher activity locations.

This report describes the results of a series of five studies conducted at the FEMP to assess the usefulness and applicability of the RTRAK to support soil remediation. An initial calibration study (1) provided data that allowed the RTRAK NaI detectors to be calibrated in order to quantify specific radionuclide concentrations. The Uranium in Soils Integrated Demonstration (USID) area study (2) and the South Field area study (3) were conducted to optimize data acquisition parameters and to delineate key data quality elements. Data were collected in the Drum Baling Area (4) to extend the characterization of the RTRAK to areas with elevated levels of radioactivity. A second calibration study (5) was conducted to extend the calibration range of the RTRAK using data from higher activity locations. The first three studies are described in the July 1997 RTRAK Applicability Study (DOE 1997b), while the fourth study was described in the September addendum to the July 1997 study. The fifth study is described in this report. These five studies set the basis for this report's analysis and discussion.

As noted above, three of the five primary COCs, total uranium, thorium-232, and radium-226, are the contaminants of analytical concern in this report. Because thorium-232 is in secular equilibrium with its radioactive daughters, the concentrations of thorium-228 and radium-228 are equal to that of thorium-232; hence there is no need for analysis of these two analytes. In addition, much of the report discusses uranium-238 concentrations rather than total uranium concentrations. Multiplying uranium-238 in pCi/g by a factor of three gives the total uranium concentration in parts per million (ppm) (assuming normally enriched uranium). **Raw RTRAK data are not included in this report because the data are so voluminous. The data are stored electronically; readers interested in accessing these data are requested to contact DOE Fernald.**

1.5 OBJECTIVES

The overall objective of this RTRAK applicability study is to delineate RTRAK system characteristics and to evaluate RTRAK system data quality parameters to determine how the RTRAK can be best used for the applications identified in Section 1.1. Specific report objectives include:

1. Describe the RTRAK system and its component subsystems;

2. Document the calibration process for RTRAK NaI detectors that enables concentrations of specific radionuclides to be calculated from raw data gathered in the field;

3. Describe and document the equations and methodologies used to quantify radionuclide concentrations from gamma photon energy spectra;

4. Identify optimal operation and data acquisition conditions;

5. Identify and define key analytical parameters that affect the known quality of data for the RTRAK system;

6. Establish values for these key parameters such that levels of uncertainty for various analyte concentrations can be estimated; and

7. Recommend guidelines for reviewing data.

1.6 RELATION TO OTHER DOCUMENTS

Figure 1-2 shows the relationship between the RTRAK Applicability Study and other key documents in the soil remediation process. The RTRAK Applicability Study is a method validation study, and thus forms the basis for analytical information to be incorporated into the User's Manual (DOE 1998a) and into the Real-Time Instrumentation Measurement Program QA/QC Plan (DOE 1998c, 1998d). Applications, strengths and limitations of the RTRAK, and other user-related information can be found in the User's Manual and are not included in this report. A detailed perspective of how the RTRAK fits into soil remediation operations is provided in the Sitewide Excavation Plan (SEP; DOE 1998b).

1.7 REPORT FORMAT

Section 1 introduces and briefly describes the RTRAK system, outlines the report scope, delineates objectives, and provides an overview of the organization of the report. Section 2 outlines the design and methodologies for the studies described in this report. Section 3 documents the detector calibration process (Objective 2). Section 4 identifies and quantifies key data quality parameters and discusses their significance with respect to decision-making (Objectives 4, 5, and 6). Section 5 recommends guidelines for reviewing RTRAK data (Objective 7).

Supporting data and technical details are provided in Appendices A and B. Appendix A contains the detailed description of the RTRAK system and the equations and methodologies used to calculate radionuclide concentrations (Objectives 1 and 3). Appendix B contains tables and figures used as the basis for data discussion and interpretation in Section 4.0.

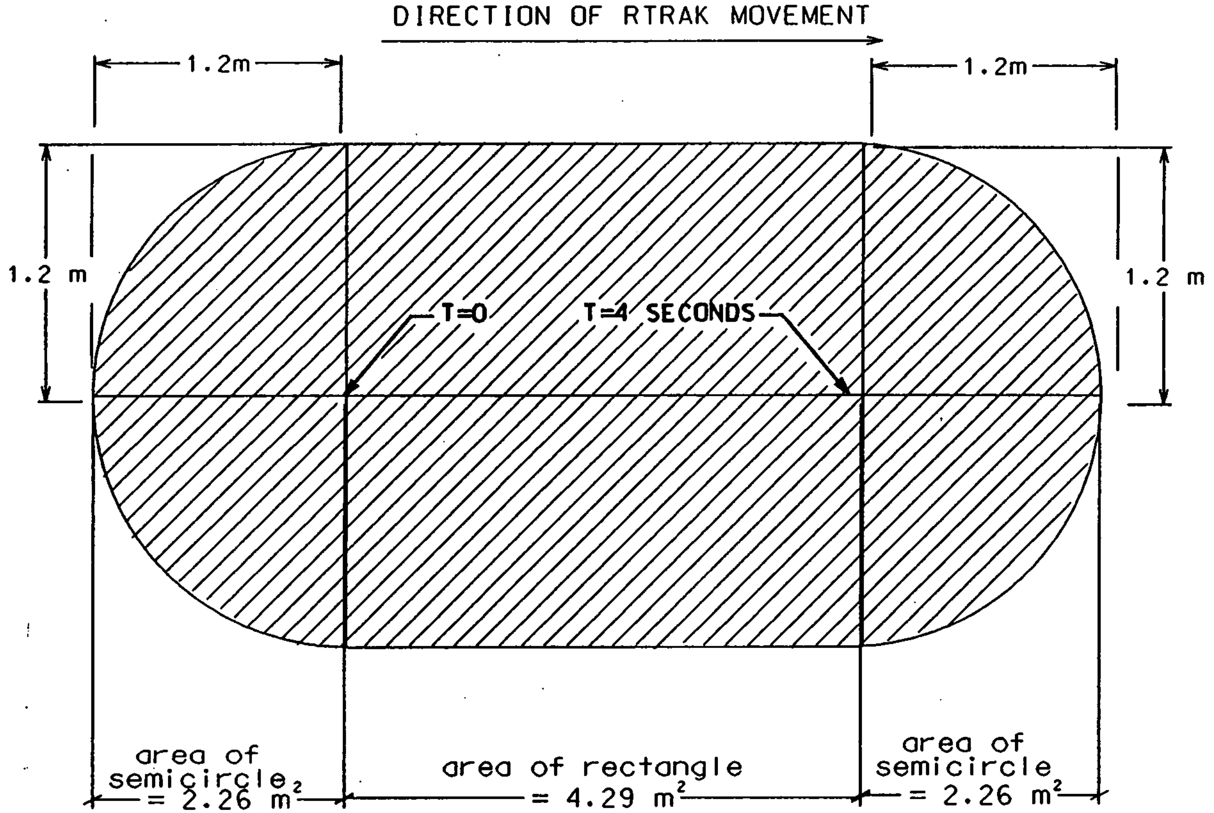
TABLE 1-1
RTRAK FIELD OF VIEW
AS A FUNCTION OF SPEED AND DATA ACQUISITION TIME

Speed	Data Acquisition Time		
(mph)	2 Seconds	4 Seconds	8 Seconds
0.5	5.6*	6.7	8.8
1.0	6.7	8.8	13.1
2.0	8.8	13.1	21.7

* Numbers represent the area of the field of view in square meters.

FIGURE 1-1.

FIELD OF VIEW OF A SINGLE RTRAK MEASUREMENT AT 1.0 MPH WITH A 4.0 SECOND DATA ACQUISITION TIME


DIRECTION OF RTRAK MOVEMENT
1.2m
1.2m
1.2 m
1.2 m
T=0
T=4 SECONDS
area of semicircle = 2.26 m²
area of rectangle = 4.29 m²
area of semicircle = 2.26 m²

▨ FIELD OF VIEW OF MEASUREMENT

FIELD OF VIEW
= 2.26 + 4.29 + 2.26
= 8.81 M

RTRAK STARTS AT T=0 AND MEASUREMENT ENDS AT T=4 SECONDS. 1.0 MPH = 0.447 M/SEC. IN 4.0 SECONDS THE RTRAK TRAVELS 1.787 METERS.

29-APR-1998

v:\5cra3dgn*bmp*calc-005.dgn

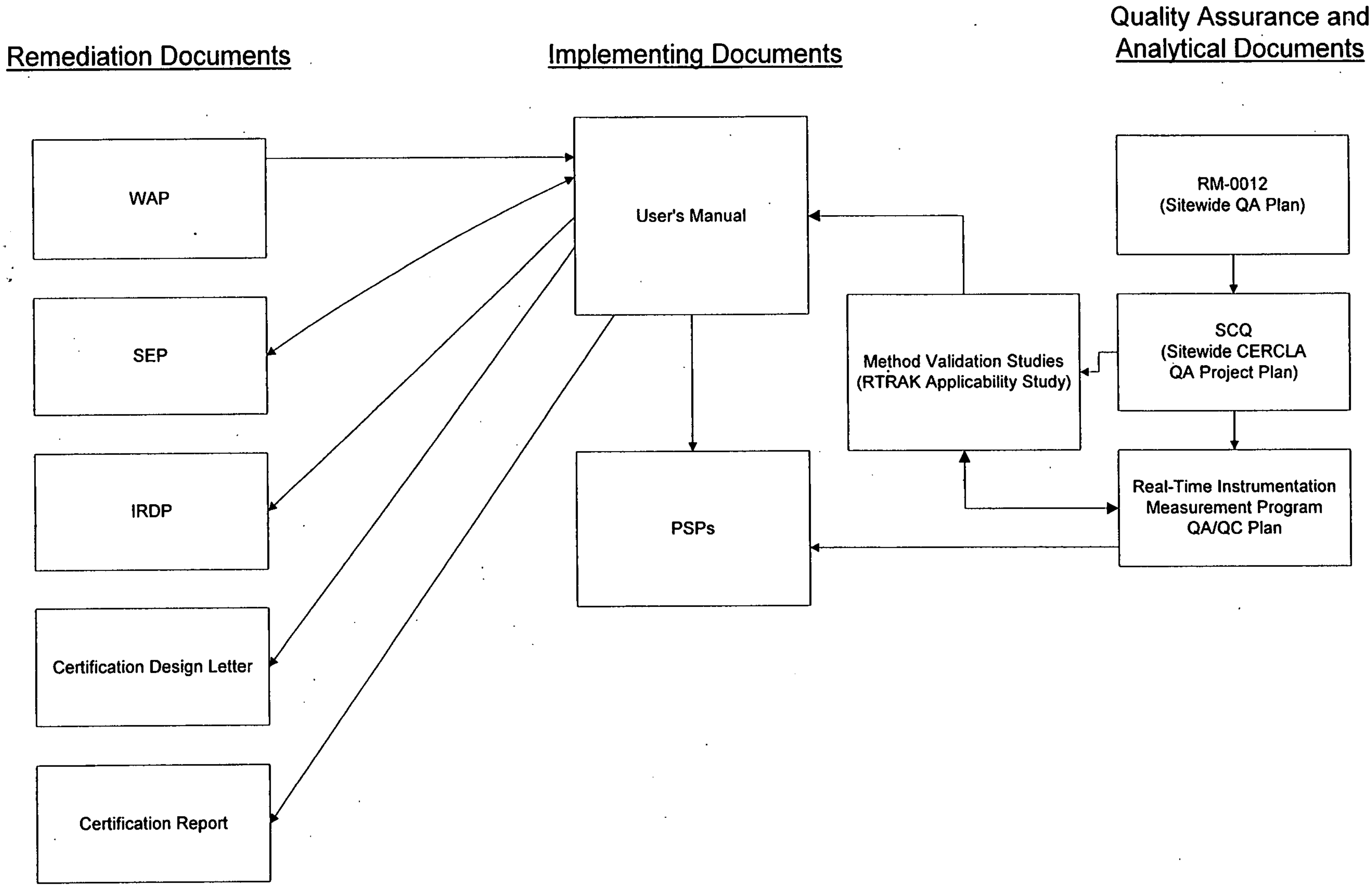

Remediation Documents
Implementing Documents
Quality Assurance and Analytical Documents
WAP
SEP
IRDP
Certification Design Letter
Certification Report
User's Manual
PSPs
Method Validation Studies (RTRAK Applicability Study)
RM-0012 (Sitewide QA Plan)
SCQ (Sitewide CERCLA QA Project Plan)
Real-Time Instrumentation Measurement Program QA/QC Plan

FIGURE 1-2 DOCUMENT RELATIONSHIPS

Section 2

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SECTION 2.0
STUDY DESIGN

2.1 TYPES OF STUDIES AND LOCATIONS

As noted in Section 1.3, the discussions and conclusions in this report are based on six separate studies. The initial calibration study, involved RTRAK measurements at each of the ten locations designated for collection of HPGe in-situ gamma spectrometry data and physical sample data for the HPGe Comparability Study (DOE 1997a). These ten locations are noted in Figure 2-1. The second study involved collection of a very large data set by making RTRAK measurements in conjunction with the Area 1 Phase I soil excavation project. The Area 1 Phase I RTRAK data locations are also noted in Figure 2-1.

The USID and South Field area studies (Figure 2-1), the third and fourth studies, were conducted to determine optimum system operating conditions and to assign values to key data quality parameters. The USID study area involved data collection over 100% of an approximately one-acre parcel of land as well as over a single track using back and forth runs. Data collection in the South Field involved RTRAK measurements along repeated runs around a circular path.

The studies in the Drum Bailing Area (fifth study) were conducted because of a recognized need to obtain data in locations with uranium concentrations approaching or exceeding the Waste Acceptance Criteria (WAC) limit and in which radium and thorium concentrations were elevated significantly above background. One of the principal goals of this study was to confirm the applicability of the RTRAK for WAC screening.

The sixth study was conducted to extend the calibration range of the RTRAK to higher radionuclide concentrations. New static RTRAK measurements and new HPGe measurements were performed in the Drum Bailing Area, the South Field, and the USID study areas to provide calibration points across a wide concentration range. Other static RTRAK and HPGe measurements were made to provide data to be used for calibration assessment. In addition, dynamic RTRAK measurements and HPGe measurements were made over a large area to provide a dynamic calibration assessment. These studies are discussed in more detail in the following sections.

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2.2.1 Calibration Studies

The objective (Section 1.4) of describing the calibration studies is to document the calibration process for RTRAK NaI detectors that enables concentrations of specific radionuclides to be calculated. The RTRAK measures the number of gamma rays per unit time detected by the NaI sensor. Regulatory limits established by the United States Environmental Protection Agency (EPA) are expressed in terms of picocuries per gram (pCi/g) for thorium-232 and radium-226, and in ppm for total uranium. RTRAK does not measure total uranium directly, but provides uranium-238 results in pCi/g. This can be converted to ppm of total uranium by multiplying by a factor of three. The process of converting counts per unit time to pCi/g is known as calibration. The calibration method for RTRAK involved making measurements at each of ten soil locations and then correlating those measurements to the known concentration of various radionuclides in the soils as measured by HPGe.

The ten areas used for the initial calibration study for the RTRAK were the same ten areas used to collect HPGe data and physical samples for the HPGe Comparability Study (DOE 1997a). Each of the ten areas was identified as a low, medium or high contamination area for uranium based on historical data and was assigned an arbitrary identification number from one to ten. Soils in low contamination areas (Areas 1, 8 and 9) were believed to contain less than 80 ppm total uranium; soils in moderate contamination areas (Areas 2, 4, 5, and 6) were believed to contain between 80 and 200 ppm total uranium; and soils in high contamination areas (Areas 3, 7 and 10) were believed to contain more than 200 ppm total uranium. However, as shown in Table 2-1, based upon physical samples collected for the HPGe Comparability Study (DOE 1997a), total uranium concentrations were generally lower than believed.

HPGe measurements were taken at each of the ten areas to provide "known" concentrations. The measurements were carried out at a detector height of 31 cm (similar to the height of the RTRAK NaI detector) using 900 second counting times. The RTRAK NaI detector was centered over the exact location as the HPGe detector and measurements were obtained using 300 second count times. RTRAK calibration data were obtained in a static mode (i.e., RTRAK stationary). As will be discussed in Section 3, the RTRAK data are correlated against "known" concentrations based upon HPGe measurements in order to derive factors for converting counts per second (cps) to pCi/g.

A second calibration study was conducted in Fall 1997 to extend the range of the calibration to higher activity concentrations. For this extension, ten additional measurements were taken at locations within the USID Area, the South Field, and the Drum Bailing Area. The locations were selected on preliminary RTRAK scans conducted in these areas. RTRAK and HPGe measurements were performed at all of the locations, and the data were collected and processed in the same manner as was done for the initial calibrations. The data from these measurements were combined with the initial calibration data to generate calibration equations that span a wide range of activities. Details of the calibration are described in Section 3.3 of this report.

2.2.2 Area 1 Phase I Measurements

Use of the RTRAK data obtained for Area 1 Phase I activities provides a large data set not otherwise readily obtainable under testing conditions. The system was used in a roving mode at a nominal speed of two miles per hour and minimum count times of two seconds. At this speed and count time, a gamma reading was made and recorded every 8.8 m^2. Before excavation, the RTRAK was used to collect measurements to determine the soil concentrations of total uranium in relation to WAC for the On-Site Disposal Facility (OSDF). After soil excavation, the RTRAK covered all excavated areas with an interlocking pattern of readings to provide as close to 100% coverage as possible. As noted in Section 1.4 (Objective 7), the primary use of RTRAK Area 1 Phase I data in this report is to provide a large data set that can be used to establish the best ways to organize and display RTRAK data for use in environmental decision-making.

2.2.3 USID and South Field Study Areas

RTRAK data collection in the USID and South Field study areas was conducted to optimize RTRAK operating parameters as well as to assign values to key data quality parameters. These studies address objectives 4, 5, and 6 (Section 1.4).

2.2.3.1 USID Study Area

The detector speed and data acquisition time studies consisted of multiple runs in the USID area north of the incinerator (see Figure 2-1). The identified testing area measured approximately one acre and was selected based on soil characterization data from previous testing and technology demonstration studies. Concentrations of uranium-238, thorium-232, radium-226, and potassium-40 were the parameters analyzed. To determine the optimal RTRAK operating parameters, three combinations of vehicle speed and detector acquisition time were used as follows:

- 2 mph at 2 second acquisition time;
- 0.5 mph at 2 second acquisition time; and
- 0.5 mph at 8 second acquisition time.

Approximately 100% of the USID study area was characterized by the RTRAK. The objective of such coverage was to obtain a data set that could be used to ascertain the effect of aggregating measurements over areas of varying size. RTRAK measurement strategy consisted of moving in a clockwise spiral going from the perimeter of the mapped area toward the center of the mapped area. Vehicle speed and detector acquisition time were adjusted before each run.

In conjunction with the RTRAK measurements, 36 HPGe measurements at a height of one meter were taken using a triangular grid layout to characterize approximately 100% of the 1-acre area, as shown schematically in Figure 2-2. The coordinates of each measurement point were established and located. Soil moisture and density measurements were performed in conjunction with each HPGe measurement to physically assess the soil conditions.

Static measurements using the RTRAK NaI system were performed at four selected locations on the grid: these locations represented two relatively high and two relatively low contamination concentration values. These locations were determined based upon review of the RTRAK and HPGe measurement results. The static RTRAK measurements were performed at acquisition time intervals of two and eight seconds for a total of 300 seconds each. The purpose of the static measurements was to assess the validity of the calibration (Section 3.3) by comparing RTRAK and HPGe data in a different area than those in which the calibration measurements were performed.

Finally, a single track RTRAK measurement profile was selected based on the above RTRAK and HPGe measurement results. This track was measured using the RTRAK system applying a repeated back and forth pass method for twenty iterations using each combination of acquisition time and vehicle speed (as described above). This allowed assessment of the total uncertainty associated with each combination of RTRAK speed and data acquisition time. The track location is shown on Figures 2-1 and 2-2.

A general description of the soil type and topography of the gridded measurement area was recorded, as well as a description of the soil type at each of the 36 HPGe measurement locations. Soil sample collection for laboratory analysis was not an aspect of this study; however, atmospheric temperature was recorded during all measurements using both RTRAK and HPGe detection systems.

2.2.3.2 South Field Study Area

RTRAK measurements were also taken in the South Field area because previous Remedial Investigation/Feasibility Study (RI/FS) and HPGe data indicated that higher radium and thorium concentrations were present there than in the USID area. This enabled optimization of RTRAK operating parameters and assignment of values to key data quality elements to be based, at least partially, on field locations with elevated contamination. Further, physical samples and HPGe measurements had been previously collected in several areas (Areas 13 and 16) in the South Field (Figure 2-3) in a continuation of the comparability study. RTRAK measurements were taken in the same locations to allow the measurements to be tied to HPGe and laboratory data in two areas.

RTRAK runs occurred along an oval-shaped track (Figures 2-1 and 2-3), with the western portion of the RTRAK run area intersecting the center of the circular Area 13, and the eastern portion of the RTRAK run area intersecting the center of the circular Area 16. The centers of these areas were the sample points in the circles directly beneath the HPGe detectors. Ten traverses of the circle were made at each of the following speeds and acquisition times:

- 2.0 mph, 2 seconds;
- 0.5 mph, 8 seconds; and
- 1.0 mph, 4 seconds.

The 1.0 mph and 4 second data acquisition time represents a compromise in operating conditions from 2.0 mph and 2 second acquisition time to 0.5 mph and 8 second acquisition time. Results from the USID area suggested that these operating conditions (1.0 mph and 4 seconds) might be the optimal ones to routinely employ.

The RTRAK study in the South Field was carried out subsequent to the South Field portion of the HPGe Comparability Study, in which certain South Field locations were measured and sampled. Because the RTRAK runs were conducted on different days and different moisture conditions than on the days that HPGe data and physical samples were calculated, Troxler moisture/density readings were re-collected at Area 13, Location 1, and at Area 16, Location 1 each day in which the RTRAK runs were conducted. Soil and air temperature and humidity readings were also recorded at the beginning of each day in which the RTRAK run is conducted. The circular RTRAK track is shown in Figures 2-1 and 2-3.

2.2.4 Drum Baling Area

RTRAK measurements were conducted in a location known as the Drum Baling Area (DBA). Past surveys in this area revealed that elevated uranium, radium-226, and thorium-232 activities could be expected. Repeated profile measurements were performed to gain a measure of the method precision (total system precision, not just precision based upon counting statistics), using three combinations of acquisition time and travel speed: 2 sec/2 mph, 4 sec/1 mph, and 8 sec/0.5 mph. The profile paths are shown in Figures 2-4 through 2-6. In addition, static RTRAK measurements and high purity germanium (HPGe) measurements were performed at three specific locations within the DBA. The static RTRAK measurements and the HPGe measurements were made to assess the accuracy of the RTRAK at higher analyte concentrations. The static RTRAK data were collected as several series of short measurements which had individual acquisition times of 2 and 8 seconds. The total acquisition period for each series of measurements was 300 seconds (summing a series of individual 2 or 8 second acquisition times for a total of 300 seconds is equivalent to a single 300 second count time).

2.2.5 Extension of RTRAK Calibration Range

The original RTRAK calibration was based on data collected during the HPGe Comparability Study (DOE 1997a). These data had limited concentration ranges; thorium-232 and radium-226 were all near FEMP background levels, and the maximum uranium-238 concentration was approximately 284 ppm (Table 2-1). Because of a desire to use the RTRAK to survey for WAC exceedances, it was considered necessary to extend the calibration range to higher radionuclide concentrations. New static RTRAK and HPGe measurements were made in the Drum Bailing Area, the South Field, and the USID Study Area. A total of eight new calibration measurements (final calibration data set consists of the ten original locations plus the eight new locations) were made in these three areas. At each calibration location, measurements were made using the RTRAK in a static mode (five-minute data acquisition time) and the HPGe (15-minute data acquisition times). Similar measurements were also made at five additional locations to be used for calibration assessment.

Full area scans (approximately 100% coverage) of a portion of the Drum Bailing Area were made using the RTRAK, and the HPGe. These data were collected for assessment of the RTRAK calibrations in the dynamic mode. The Drum Bailing Area was selected for this assessment because it has considerably higher radionuclide concentrations than the USID and South Field Study Areas and is more heterogeneous. Because these measurements help evaluate the applicability of the RTRAK in high activity heterogeneous locations, they also provide data on the accuracy of the system in heterogeneous locations.

TABLE 2-1
TOTAL URANIUM CONCENTRATIONS IN TEN AREAS USED FOR ORIGINAL RTRAK CALIBRATION

Area	Number of Samples *	Average and Standard Deviation of Total Uranium Concentration (ppm) Based upon Alpha Spectrometry
PBC-01	6	7.4 ± 0.9
PBC-02	10	26 ± 5
PBC-03**	14	284 ± 69
PBC-04	10	55 ± 10
PBC-05	10	46 ± 18
PBC-06	10	88 ± 13
PBC-07	15	179 ± 56
PBC-08	6	5.0 ± 1.4
PBC-09	6	6.3 ± 0.7
PBC-10	15	54 ± 14

* excluding duplicates

** excluding PBC-03-1

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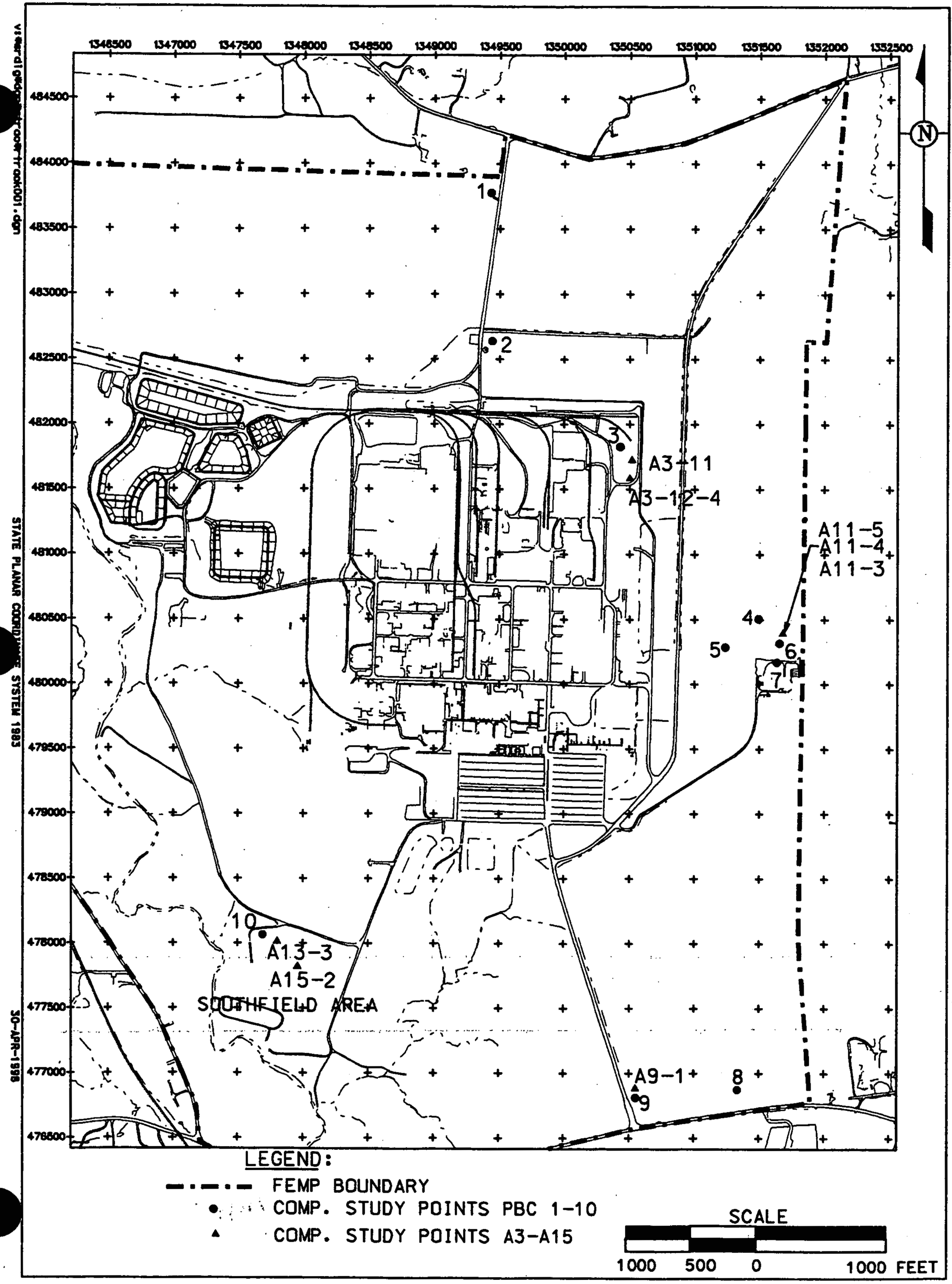
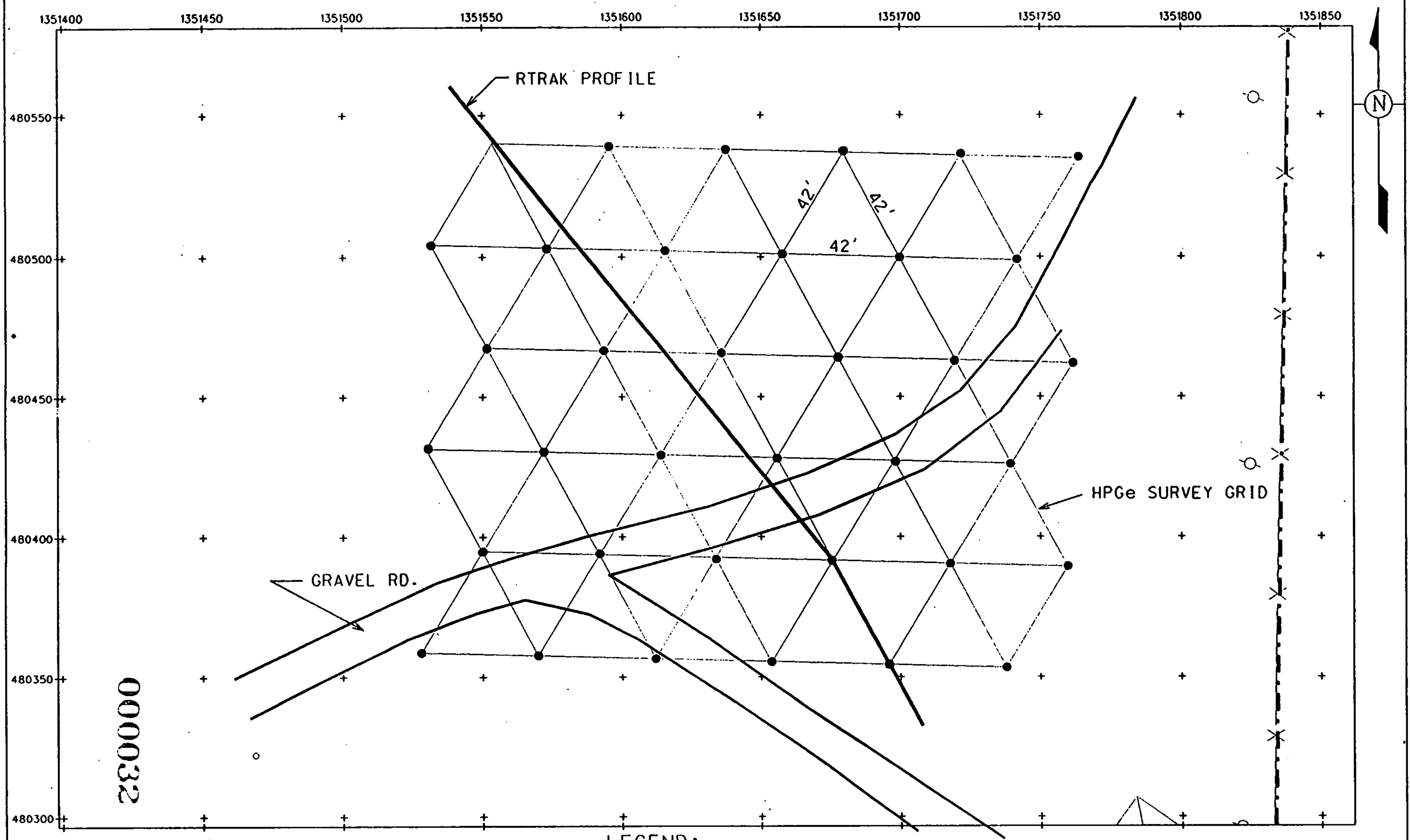


v:\fsrdlgk\...\trook001.dgn
STATE PLANAR COORDINATE SYSTEM 1983
30-APR-1998
1346500
1347000
1347500
1348000
1348500
1349000
1349500
1350000
1350500
1351000
1351500
1352000
1352500
484500
484000
483500
483000
482500
482000
481500
481000
480500
480000
479500
479000
478500
478000
477500
477000
476500
N
1
2
3
A3-11
A3-12-4
A11-5
A11-4
A11-3
4
5
6
7
10
A13-3
A15-2
SOUTHFIELD AREA
A9-1
8
9
LEGEND:
FEMP BOUNDARY
● COMP. STUDY POINTS PBC 1-10
▲ COMP. STUDY POINTS A3-A15
SCALE
1000
500
0
1000 FEET

FIGURE 2-1. RTRAK CALIBRATION LOCATIONS


1351400
1351450
1351500
1351550
1351600
1351650
1351700
1351750
1351800
1351850
480550
480500
480450
480400
480350
480300
N
RTRAK PROFILE
42'
42'
42'
HPGe SURVEY GRID
GRAVEL RD.

LEGEND:

- – · – · – FEMP BOUNDARY
- ● HPGe MEASUREMENT POINTS
- ——— [illegible]AK PROFILE

SCALE
50 25 0 [illegible]FEET

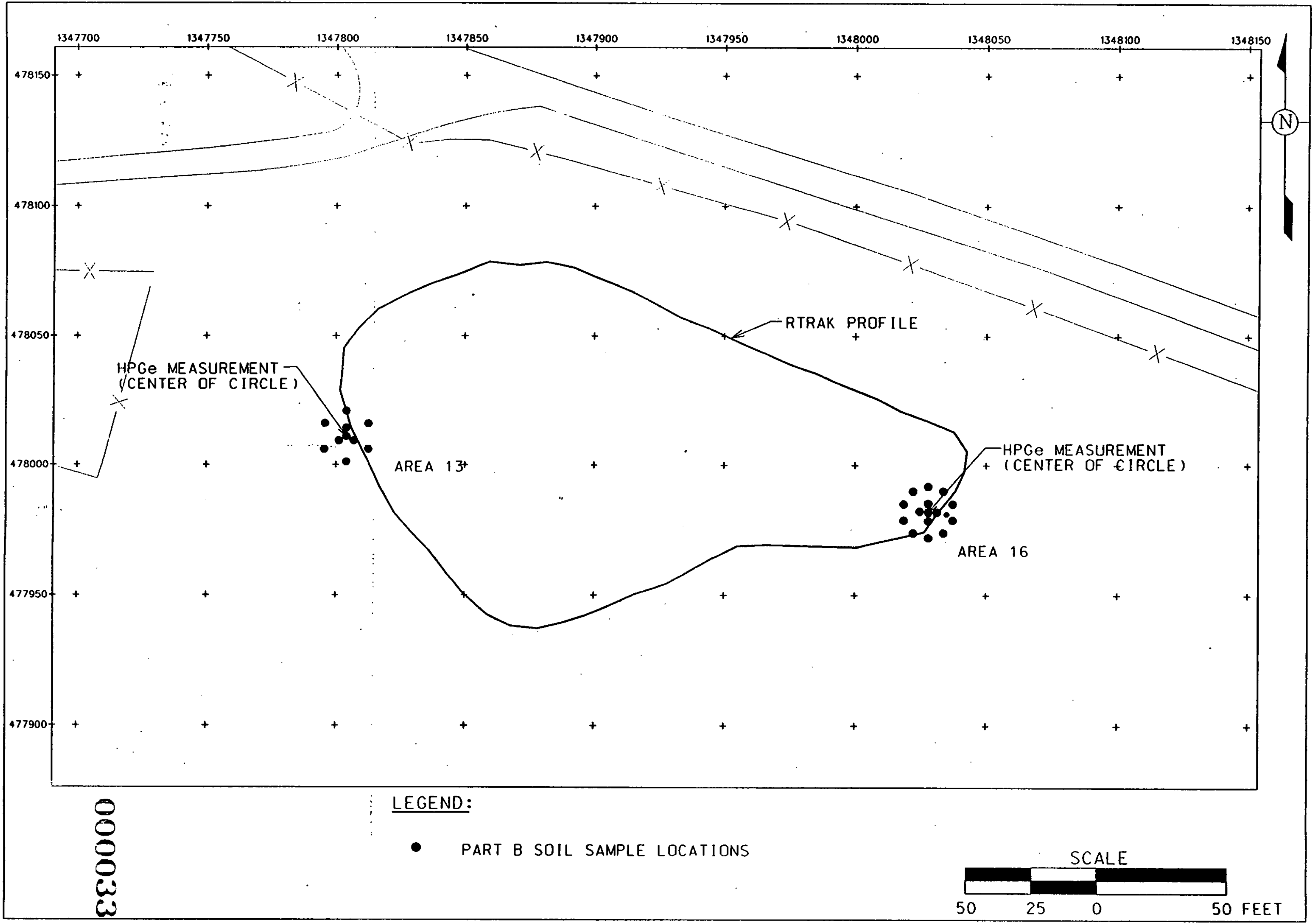
000032

1420

c:*mge*srdig*c[illegible]rtrc003.dgn
STATE PLANAR CO[illegible]INATE SYSTEM 1983

26-JUN-1997

FIGURE 2-2. RTRA[illegible]ND USID TEST AREA


1347700
1347750
1347800
1347850
1347900
1347950
1348000
1348050
1348100
1348150
478150
478100
478050
478000
477950
477900
N
RTRAK PROFILE
HPGe MEASUREMENT
(CENTER OF CIRCLE)
AREA 13
HPGe MEASUREMENT
(CENTER OF CIRCLE)
AREA 16
LEGEND:
● PART B SOIL SAMPLE LOCATIONS
SCALE
50
25
0
50 FEET

c:*mge*srdig*dgn*bmp*rtrc002.dgn
STATE PLANAR COORDINATE SYSTEM 1983

26-JUN-1997

FIGURE 2-3. RTRAK PROFILE RUN IN THE SOUTHFIELD

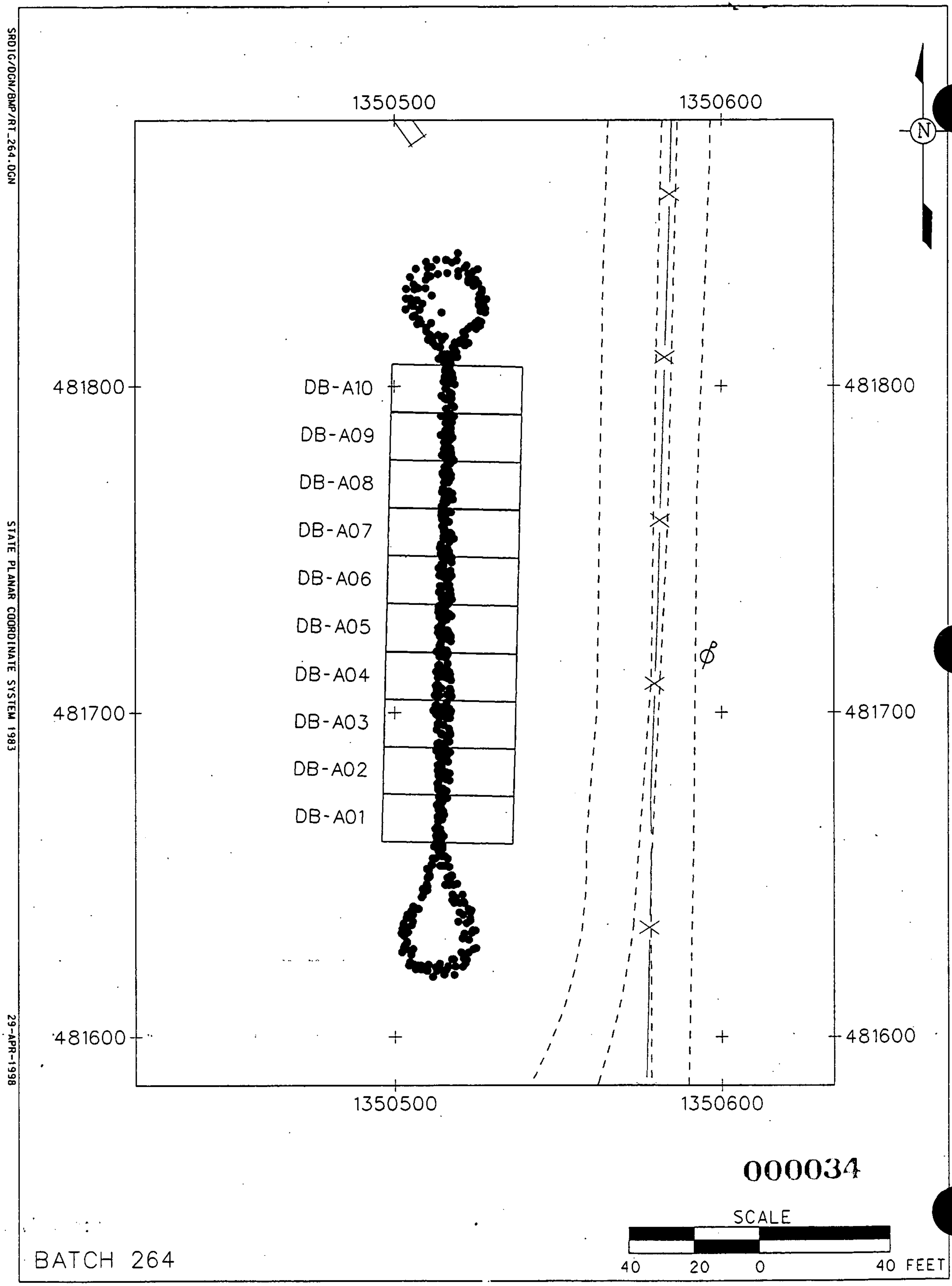

SRDIG/DGN/BMP/RT_264.DGN
STATE PLANAR COORDINATE SYSTEM 1983
29-APR-1998
1350500
1350600
N
481800
481700
481600
DB-A10
DB-A09
DB-A08
DB-A07
DB-A06
DB-A05
DB-A04
DB-A03
DB-A02
DB-A01
SCALE
40
20
0
40 FEET
BATCH 264

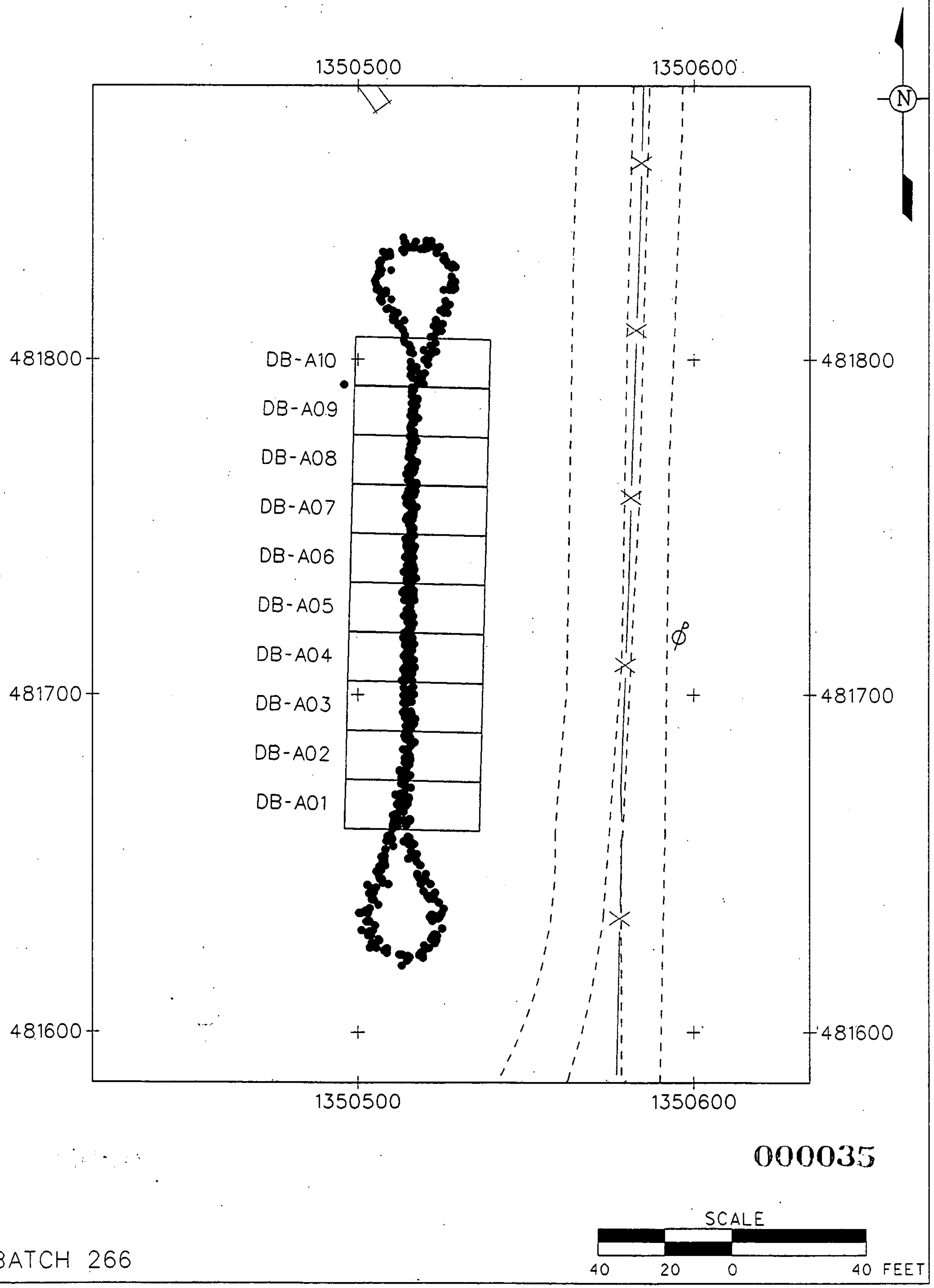
FIGURE 2-4. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR DRUM BALING AREA - 2 M.P.H./ 2 SEC. ACQUISITION

1430

SRDIG/DGN/BMP/RT.266.DGN

STATE PLANAR COORDINATE SYSTEM 1983

29-APR-1998


1350500
1350600
N
481800
481700
481600
DB-A10
DB-A09
DB-A08
DB-A07
DB-A06
DB-A05
DB-A04
DB-A03
DB-A02
DB-A01
SCALE
40
20
0
40 FEET

BATCH 266

FIGURE 2-5. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR DRUM BALING AREA - 1 M.P.H./ 4 SEC. ACQUISITION

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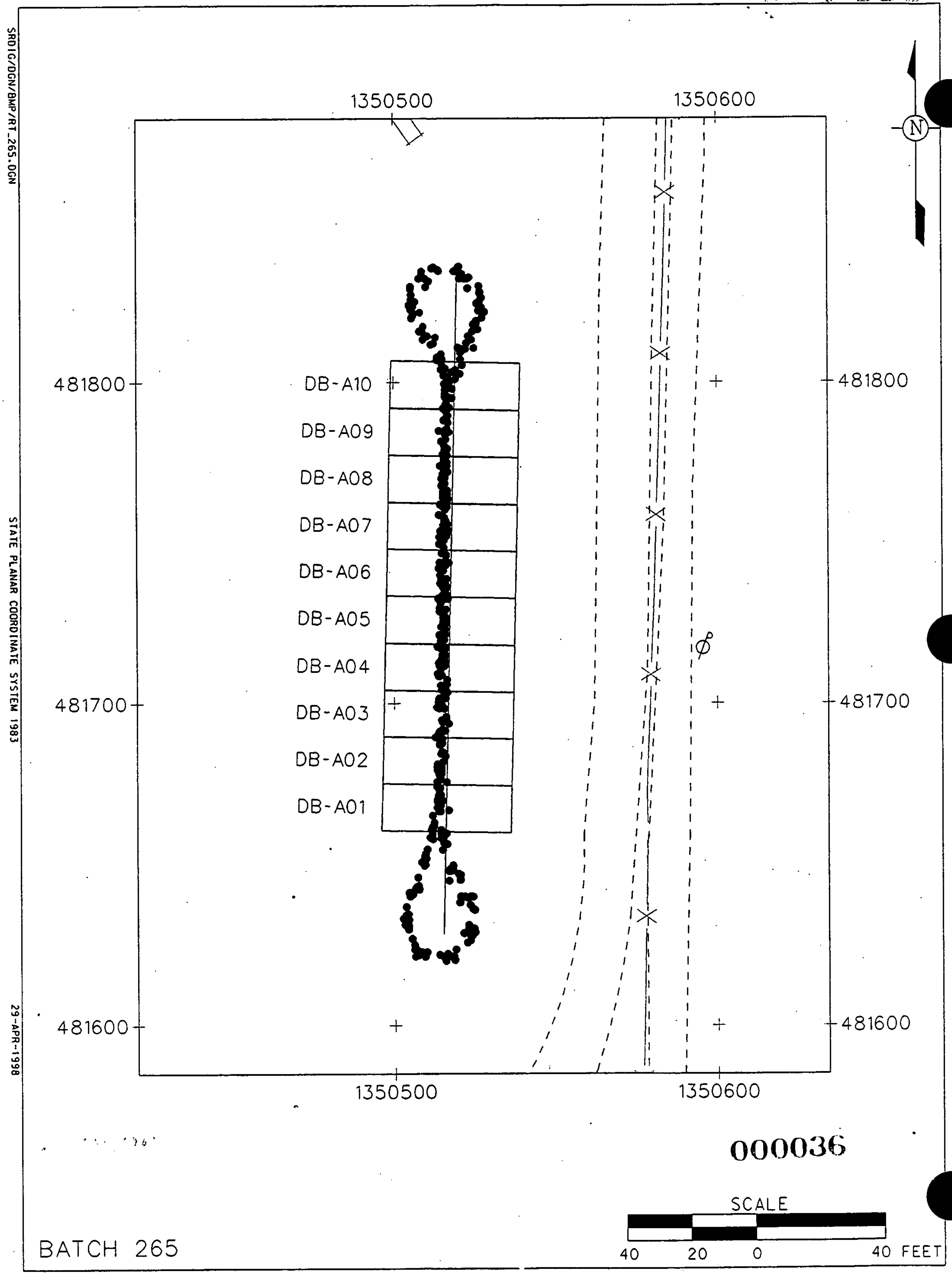
SRDIG/DGN/BMP/RT_265.DGN
STATE PLANAR COORDINATE SYSTEM 1983
29-APR-1998
N
1350500
1350600
481800
481700
481600
DB-A10
DB-A09
DB-A08
DB-A07
DB-A06
DB-A05
DB-A04
DB-A03
DB-A02
DB-A01
BATCH 265
SCALE
40
20
0
40 FEET

FIGURE 2-6. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR DRUM BALING AREA - 0.5 M.P.H./ 8 SEC. ACQUISITION

Section 3

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SECTION 3.0
CALIBRATION OF RTRAK SODIUM IODIDE DETECTORS

3.1 DETECTOR CALIBRATIONS

This section describes the process by which the sodium iodide (NaI) gamma ray detector mounted on the RTRAK vehicle is calibrated. It also presents the "calibration equations" which are the end result of the calibration process. With these calibration equations, the net counts registered by the sodium iodide detector from a particular isotope may be used to calculate the concentration, i.e. the activity per unit mass, of that radionuclide in the soil which was scanned by the RTRAK. One of the reasons for updating the July, 1997 RTRAK Applicability Study was to extend the calibration range to higher analyte concentrations. The results of this process will be discussed.

Two calibrations are required on a gamma-ray counting system in order to qualitatively and quantitatively evaluate the spectrum. These two calibrations are (1) an energy calibration, which permits identification of nuclides in the sample on the basis of the energy of gamma photon peaks in the spectrum, and (2) an efficiency calibration, which converts the relative counts in the spectrum to activity concentrations in pCi/g. This section of the report briefly describes the energy calibration process and documents the efficiency calibration process for the RTRAK in considerable detail.

3.2 ENERGY CALIBRATION

The energy calibration process is described in FEMP procedure EQT-30, "Operation of Radiation Tracking Vehicle Sodium Iodide Detection System." This procedure addresses the use of calibration sources containing radionuclides of known gamma energies to generate an energy calibration "curve." In the case of the RTRAK, a thorium-containing lantern mantle emits gamma photons for thorium-232 daughters at 238.6 keV and 2615 keV. The system amplifier is adjusted so that the 238.6 keV photon is assigned to channel 40 in the multichannel analyzer, and so that the 2615 keV photon is assigned to channel 447. On average each channel corresponds to approximately 5.9 keV; thus, other gamma photons are linearly distributed to channels in the multichannel analyzer on the basis of their energy. Performance checks ensure that the two energies (238.6 and 2615 keV) always occur at channel 40 ± 2 and channel 447 ± 2, respectively. Refer to Appendix A for more detail about the energy calibration process.

3.3 EFFICIENCY CALIBRATION

After properly completing an energy calibration, the NaI detector can be used to determine the identity of the radioisotopes in the soil scanned by the RTRAK provided that the photon energies are at least 70 keV apart (see Appendix A). However, in order to use the RTRAK to also determine the quantity of each radionuclide which is present, the number of gamma ray counts of a particular energy registered by the counter must be related to the amount of that radionuclide present in the soil. This process is called efficiency calibration.

Because the RTRAK was designed as an in-situ measurement system, it is not practical to use certified standard reference materials to calibrate the detector as one would in a laboratory setting. Therefore, the RTRAK efficiency calibration procedure involved making comparative RTRAK and HPGe measurements at eighteen different soil areas containing known concentrations of radionuclides and performing multiple linear regression analyses of the soil concentration (as measured by HPGe) versus the net RTRAK gamma count rates. At each measurement location, the RTRAK and the HPGe detectors were placed at the same position coordinates within the accuracy limits of the GPS satellite positioning system. Fifteen minute HPGe spectra and five minute RTRAK spectra were acquired at each location. The HPGe detector was positioned at height of 31 cm to approximate the RTRAK detector field of view. The data which were used to develop RTRAK calibration equations are shown in Appendix A, Table A-2. It consists of data collected at the ten field locations used in the HPGe Comparability Study (DOE 1997a) plus an additional eight locations in the Drum Baling, South Field, and USID areas of the FEMP. The measurement locations in the Drum Baling area were chosen to extend the calibration range to higher radionuclide concentrations. In most cases the RTRAK and HPGe data displayed in Table A-2 are averages of two or more measurements. Since HPGe measurements were shown by a series of reports issued in 1997 (Section 1.3) to be accurate and comparable to laboratory analyses, the HPGe measurements were used as the basis for "known" concentrations of U-238, Th-232, and Ra-226.

In Revision 0 of the RTRAK Applicability Study issued in July 1997 (DOE 1997b), only simple linear regressions were required to derive Ra-226 and Th-232 calibration equations, whereas multiple linear regression was necessary to accurately represent the uranium data. When higher radionuclide concentrations are present, interferences not evident in the earlier study became apparent, and it

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became necessary to use multiple linear regressions to derive the calibration equations for all three isotopes. In general, the multiple linear regression equation will have the form:

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3$$

where x_1, x_2, and x_3 are RTRAK net count rates for the three isotopes of interest and b_0, b_1, b_2, and b_3 are the coefficients derived from the multiple linear regression analysis which give the "best fit" to the data in Table A-2. For U-238 it is necessary to use all three variables (x_i terms) in the equation above; but Th-232 and Ra-226 require the use of only two variables. Each isotope will be discussed separately below.

The gamma ray spectrum generated by the RTRAK system is processed by integrating the counts in the spectrum across specific energy regions of interest. These regions are associated with the energies of gamma rays emitted by the analytes of interest and with energies considered to be representative of the spectrum background associated with each analyte. The net counts for an analyte are obtained by subtracting the spectrum background contribution from the appropriate energy region of interest. The regions of interest are addressed in Appendix A, Section A.5.1. Net counts per second are calculated by dividing the net counts by the data acquisition time.

Thorium-232 Calibration Equation

The Th-232 calibration equation involves a radium term as well as a thorium term because emissions from Ra-226 daughters effect the RTRAK thorium result by contributing counts to the thorium signal window. This interference becomes important at higher radium concentrations. Multiple linear regression analysis involving Th-232 and Ra-226 net count rates versus HPGe Th-232 measurements yields the following calibration equation:

$$\text{RTRAK Th-232 pCi/g} = 0.05725481*\text{Th}_{NCPS} - 0.0044179*\text{Ra}_{NCPS} + 0.09624421$$

The radium term in this equation is negative to compensate for contributing non-thorium counts in the signal window. When both radium-226 and thorium-232 counts are zero, the equation has an intercept of 0.096 pCi/g, which is acceptably close to zero.

Radium-226 Calibration Equation

Low abundance gamma rays from Th-232 daughters contribute counts to the background windows for Ra-226. If this interference was ignored, the normal mode of background correction would overcompensate, thus yielding Ra-226 results biased low. Multiple linear regression analysis involving Th-232 and Ra-226 net count rates versus HPGe Ra-226 measurements yields the following calibration equation:

$$\text{RTRAK Ra-226 pCi/g} = 0.12145634 * \text{Ra}_{\text{NCPS}} + 0.01735413 * \text{Th}_{\text{NCPS}} + 0.13277316$$

The thorium term in the Ra-226 equation is positive to compensate for the overcorrection of the background. When both radium-226 and thorium-232 counts are zero, the equation has an intercept of 0.13 pCi/g for radium-226, which is acceptably close to zero.

Uranium Calibration Equation

Two equations are provided for uranium, thereby allowing uranium to be calculated as either pCi/g of uranium-228 or as ppm of total uranium. The second equation is derived from the first by making use of known constants and weight to activity conversion factors, and further assuming that the uranium encountered in the soil will be of normal enrichment.

Uranium experiences interferences in both the signal window and the background windows. Th-232 daughter gamma rays at 969 Kev contribute to the signal window, while Ra-226 daughter gamma rays at 1120 Kev contribute to the background window. Thus a term proportional to the Th-232 activity must be subtracted from the counts in the signal window, while a term proportional to the Ra-226 activity must be added back in to compensate for the overcorrection due to the elevated background counts. Multiple linear regression analysis involving U-238, Th-232 and Ra-226 net count rates versus HPGe U-238 measurements yields the following equations:

$$\text{RTRAK U-238 pCi/g} = 0.95562898 * \text{U}_{\text{NCPS}} - 0.4031465 * \text{Th}_{\text{NCPS}} + 1.01951125 * \text{Ra}_{\text{NCPS}} + 9.408$$

$$\text{RTRAK Total U ppm} = 2.86307076 * \text{U}_{\text{NCPS}} - 1.20782959 * \text{Th}_{\text{NCPS}} + 3.05446247 * \text{Ra}_{\text{NCPS}} + 28.186$$

Figures 3-1 through 3-3 display the results of the multiple linear regression analyses for Th-232, Ra-226 and U-238 respectively. In each figure, HPGe results are plotted on the x-axis and the calculated RTRAK results based on the multiple linear regression calibration equation for the corresponding isotope are plotted on the y-axis. The calibration equation is displayed on each graph along with the square of the correlation coefficient for the multiple linear regression. Values of R^2 near one indicate the degree to which the equation represents the data. For all three isotopes, R^2 exceeds 0.95 which indicates excellent correlation. In addition to using R^2 as a gauge of the reasonableness of the calibration equation, the intercept is also important. This tells what the calibration equation would predict for the soil activity when all the net count rates in a given equation are zero. Ideally, this intercept should be zero. So, a calibration equation having an intercept near zero is another criterion that can be used to judge reasonableness. All three calibration equations satisfy this criterion also. The uranium calibration equations have the largest intercept of the three: 9.4 pCi/g or 28.2 ppm. While these values are not ideal, they will not effect the use of RTRAK in any practical way because they are approximately one third of the uranium FRL of 82 ppm, and are far below the WAC of 1030 ppm. In any event, the RTRAK will not be used to decide if a given area is below FRL.

If there were perfect agreement between the HPGe results and the RTRAK results based on the calibration equations, all the plotted points would fall on a straight line which had a slope of one. A solid line with a slope of one has been added to each graph (Figure 3-1 through 3-3). This line does not represent a best fit or regression line. It was added to help the reader judge the goodness of the calibration. One can see that while the data on each graph spans a fairly wide range, most of the data points fall near the "slope of one" line. On a percentage basis, the differences between HPGe and RTRAK results are no larger at high analyte concentrations than they are at low concentrations.

In order to assess the uncertainty associated with the new calibrations, one can look at the differences between the measured HPGe isotopic concentrations and the values calculated by use of the new RTRAK calibration equations. The absolute differences display variations from point to point, but the differences in pCi/g become successively larger from thorium-232 to radium-226 and then to uranium-238. This same trend holds true when evaluating the data on a percentage basis, using the HPGe results as the known values. For each isotope, there are instances where the RTRAK calibration yields larger results than the corresponding HPGe values, and other instances where the RTRAK equation predicts values lower than the HPGe measurement. To make an overall assessment of the differences, the average percent difference between RTRAK and HPGe has been computed. This has been done for the three isotopes of concern. Whether the differences are positive or negative is immaterial; therefore, the averages of the absolute values of the percent differences were computed. For thorium-232, radium-226 and uranium-238 respectively, the percent differences are 9.0%, 14.8% and 23.8%. The RTRAK uranium-238 equation will not agree with HPGe results below 9.4 pCi/g, the intercept of the RTRAK equation; therefore, data points with HPGe readings below this value were omitted before computing the average absolute percent difference for uranium-238. The values for the average absolute percent differences stated above may be considered estimates for each isotope of the overall uncertainty associated with the calibration process. In agreement with material presented elsewhere in this report, it can be stated that thorium-232 measurements are most accurate, followed next by radium-226 measurements and then by uranium-238 measurements.

3.4 COMPARISON TO PREVIOUS RTRAK CALIBRATION EQUATIONS

As explained above, when the RTRAK calibration was extended to higher analyte concentrations, the form of the calibration equations changed slightly. This occurred because low abundance gamma rays in the radium and thorium decay chains become more significant at higher radium-226 and thorium-232 concentrations. The origin of these interferences was explained earlier in this section.

Both the old and the new calibration equations are presented in Appendix A, because much of the data presented in this report was developed using the old equations. Because the previous calibration equations were expressed in a different form, a direct comparison with the new equations is not very revealing. However, the following generalizations can be stated. The coefficient of the thorium net counts per second term in the new thorium equation did not change substantially; 0.05825481 as compared to the old coefficient of 0.06817. The value of the intercept changed from -0.041 to +0.0924421. Such changes are not unexpected when a new variable, radium-226 net counts per second, is added to the regression analysis. Similar changes may be noted in the radium-226 equation. The old slope and intercept values were 0.19243 and 0.08805, respectively. In the new calibration equation, the corresponding values are 0.12145634 and 0.13277316, respectively. A direct comparison of the coefficients in the new and old uranium-238 calibration equations is less revealing because the new equation was formulated directly in terms of radium and thorium net counts per second rather than in pCi/g of radium-226 and thorium-232.

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However, processing RTRAK raw data using both sets of equations will provide the desired comparisons. This was done for two separate sets of data: one set of seven five-minute static RTRAK measurements from the Drum Baling Area and another set of 538 moving RTRAK measurements performed in the USID area with an 8-second acquisition time and a scanning speed of 0.5 miles per hour. The seven measurements in the Drum Baling Area were supplemented by 15-minute HPGe readings at the same locations with a detector height of 31 cm. The following general trends are noted from a review of these two data sets:

1. In terms of the differences, the agreement between the old and the new calibration equations is best for thorium. In many cases, the differences are on the order of 0.1 pCi/g or less, although on a percentage basis, some differences exceed 25% (typically at low thorium concentrations).

2. The radium agreement is second best. Typical differences which arise from the use of the two calibration equations for radium-226 are 0.3 pCi/g and less.

3. Uranium-238 differences are sometimes quite large on an absolute as well as on a percentage basis. For uranium-238 the greatest discrepancies occur when there are significantly elevated thorium-232 and/or radium-226 counts in the spectrum. These trends are not surprising since the uranium signal and background spectral regions are subject to the most interferences. (See Section 5 for a discussion of interference effects.)

4. For low uranium concentrations, the new uranium-238 equation tends to give higher results than the old equation. This is artifact of the value of the intercept (9.408 pCi/g) derived from the regression analysis. As stated several other times in this report, however, RTRAK single measurements are not reliable at uranium concentrations below the FRL because of the poor degree of precision.

5. Once the uranium-238 concentrations exceed two times the value of the regression intercept, approximately 19 pCi/g, the new calibration equation tends to yield lower uranium-238 results. This is because the new equation for uranium-238 does a better job of accounting for the spectral interferences.

6. For the set of seven data points where coincident HPGe measurements were made, five of the seven RTRAK uranium-238 results derived from the new calibration equation agreed more closely with the HPGe results than did the corresponding values computed with the old equation.

It can be seen from the above that the old and new equations for all three isotopes are similar, and yield generally similar results in the domain of low analyte concentrations where the old equations were known to apply. The one exception is for uranium-238 concentrations less than 9.4 pCi/g. Because this is the value of the intercept in the new equation, uranium-238 values calculated with the new

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equation will not agree very well with the old equation when uranium-238 concentrations are lower than 9.4 pCi/g.

3.5 USE OF CALIBRATION EQUATIONS

In a radioanalytical laboratory, the normal practice is to recalibrate gamma spectrometry systems once per year. Before using the new calibration, it is good practice to compare the old and new calibration equations to see if they agree with one another. If they are significantly different, the causes of the discrepancies should be investigated to assure that the new calibration is valid. After approving the new calibration, the laboratory discontinues use of the old calibration. Unless errors in the old calibration are discovered, the laboratory does not use the new calibration equation to recalculate results that were originally generated with the old equation.

Ana analogous situation exists with the RTRAK calibration equations. A new calibration was performed and compared to the previous one. As described in Section 3.4, the differences were investigated and found to be reasonable under the circumstances surrounding the new calibration. Therefore, the new calibration equations will be placed into service with the issuance of this report. Much of the data discussed in Section 4 of this report were generated using the old calibration equations. Since these equations were judged to be valid within the range of analyte concentrations that were encountered at the time, these results will not be recalculated with the new calibration equations. To be very specific, the data in Section 4 of this report on RTRAK system precision, accuracy, total measurement uncertainty, spatial averaging and minimum detectable activity were developed using the old calibration equations. The one exception to this statement is the data displayed in Table 4-8, which were computed using the new calibration equations. Since the old and new calibration equations yield generally similar results, especially in the domain of low analyte concentrations, one would not expect significant changes in the data presented in Section 4 of this report even if all the tabulated data in Section 4 had been recalculated using the new equations.

3.6 SUMMARY

Two calibrations are performed on the RTRAK system. An energy calibration allows identification of gamma photons on the basis of their energy. This makes it possible to qualitatively identify gamma emitting radionuclides in the soil that is being scanned. An efficiency calibration supplies factors to convert detector response in the form of counts per second to soil activity concentrations in pCi/g.

These conversion factors have been determined from multiple linear regressions of RTRAK measurements against HPGe measurements in soil areas having known concentrations of various radionuclides. These conversion factors have been used to obtain the RTRAK activity concentrations discussed in succeeding sections of this report.

Figure 3-1
COMPARISON OF RTRAK & HPGE Th-232 RESULTS

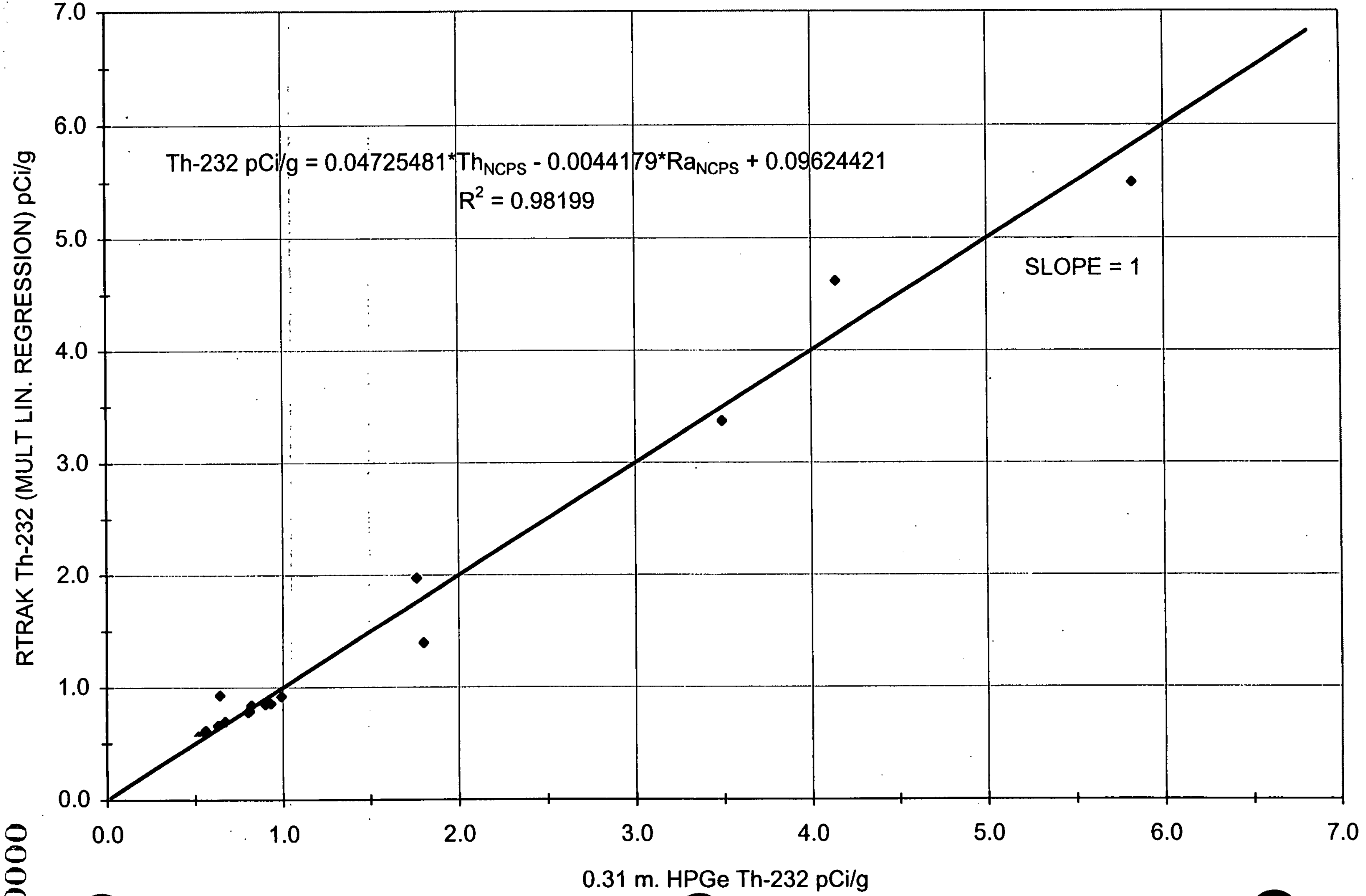


Figure 3-2
COMPARISON OF RTRAK & HPGe Ra-226 RESULTS

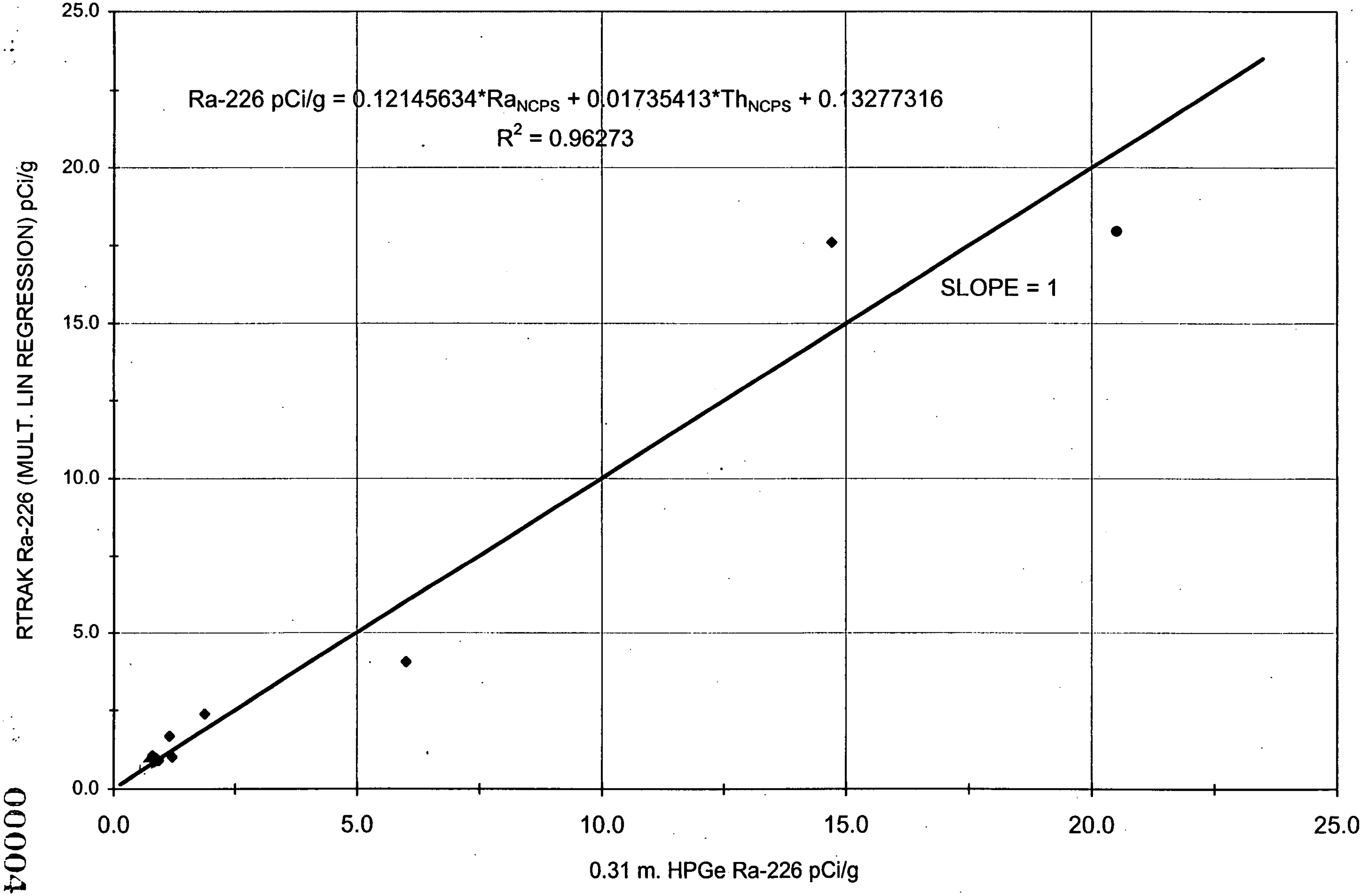
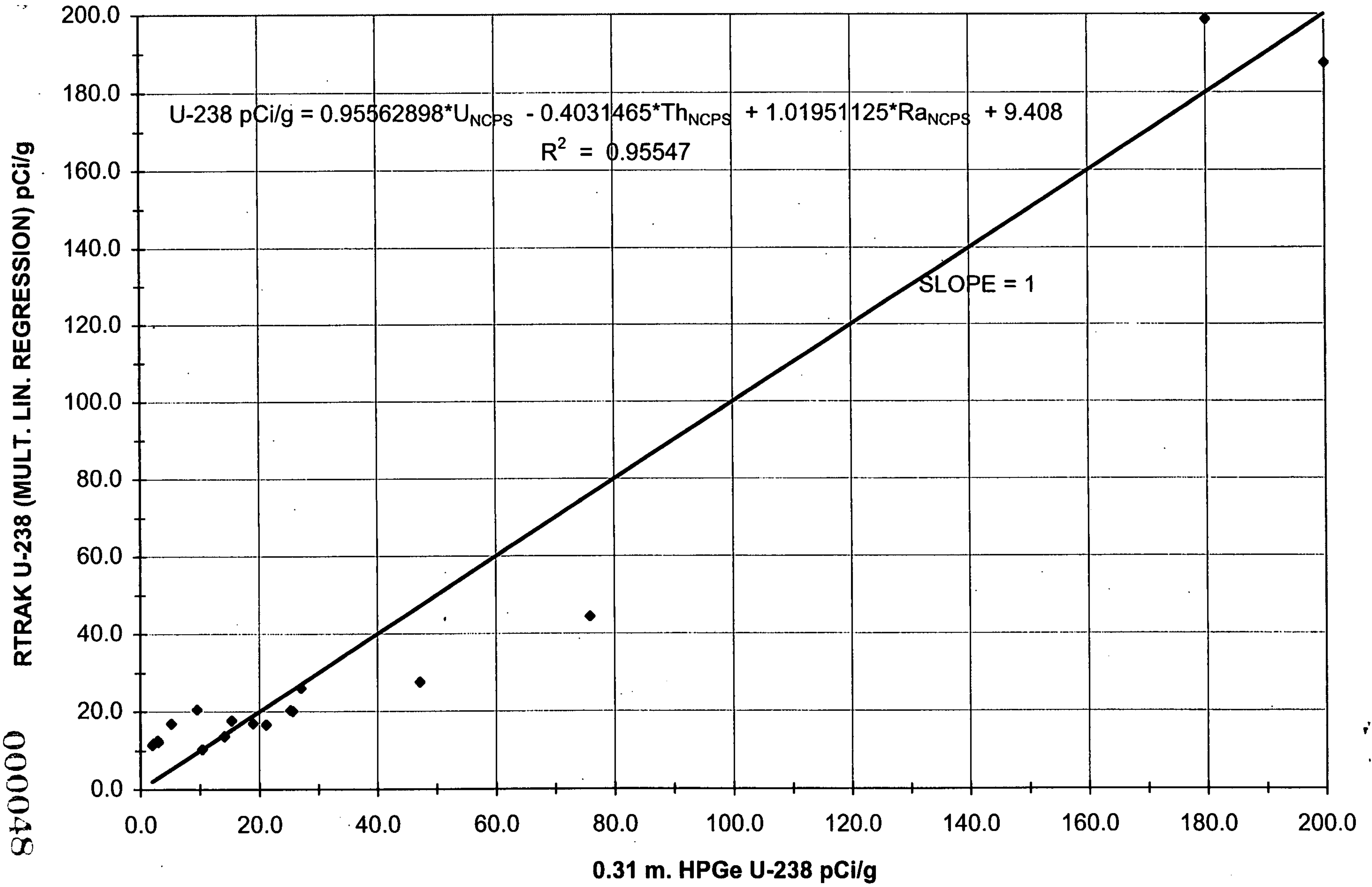


Figure 3-3
COMPARISON OF RTRAK & HPGe U-238 RESULTS



Section 4

SECTION 4.0
RTRAK SYSTEM QUALITY PARAMETERS

The RTRAK must generate data of known quality for it to be used in environmental decision-making. Three key data quality elements are examined in this Section: precision, minimum detectable concentration (MDC), and accuracy. Different combinations of tractor speed and data acquisition time are evaluated in order to delineate acceptable precision and MDCs. In addition, comparisons were made with HPGe measurements as a measure of the accuracy of the RTRAK system. Overall system quality parameters are based upon data taken from iterative runs along three profiles in three areas (one profile per area) and HPGe measurements made in those same areas.

4.1 SYSTEM PRECISION

4.1.1 Contributions to Precision

Precision may be defined as the closeness in agreement of replicate measurements. In most of the discussion that follows, precision is addressed in terms of uncertainty (expressed as a standard deviation): the higher the degree of uncertainty (larger the standard deviation), the poorer the precision. For techniques based on measuring radiation, there are three primary elements that contribute to the overall precision or uncertainty of the measurement: (1) uncertainties associated with the nature of radioactive decay (typically called counting uncertainty), (2) uncertainty associated with system electronic components (including calibration errors), and (3) other measurement uncertainty. Analyte heterogeneity in the study area is not included here for the overall estimate of uncertainty because the focus of this report is on the measurement uncertainty and the heterogeneity is analogous to sampling uncertainty for discrete sampling. Heterogeneity is discussed further in a later section of this report.

4.1.1.1 Counting Uncertainty

The total counting uncertainty comprises contributions from three sources: uncertainty of the total peak counts in the energy region of interest, the uncertainty of the counts in the spectrum background, and interferences associated with gamma rays from radionuclides other than those of interest. The counting uncertainty for the net counts for the analyte of interest is expressed as:

$$\sigma=\sqrt{m_1+m_2+m_3}$$

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where σ is the standard deviation of the net number of counts for the analyte of interest and m_1, m_2, and m_3 are, respectively, the total peak counts in the energy region of interest, background counts in that area, and counts from interfering gamma rays. From the form of this equation, it can be seen that as each contribution to total counts increases (i.e., total peak counts, spectrum background, and interference), the uncertainty due to that contribution increases and the total uncertainty increases. However, the fractional uncertainty (σ as a percentage of the concentration) will decrease with an increase in counts associated with the analyte, because σ increases as a function of the square root of m_1 while concentration is a linear function of m_1. Contributions from the background and interferences become less significant as the concentration of a given analyte increases and the relative uncertainty will decrease; this presumes that there are no other factors that increase either the background or interferences. However, in cases where the background or interfering counts increase more rapidly than analyte counts, the relative uncertainty would increase.

Uncertainty Due to Spectrum Background

Spectrum background is the portion of a gamma ray spectrum beneath the peak of interest (Figure A-1, Appendix A). It is referred to as the "continuum" that occurs beneath peaks observed in a gamma spectrum. A principal component of the continuum is Compton scattering (the interaction of gamma rays with electrons resulting in imparting of energy to the electron and a deflection of the incident gamma ray with an attendant decrease in its energy). Any gamma ray that has a higher energy than those of analytical interest will contribute to the background continuum in the energy region of interest. For example, for uranium-238, the background continuum will be affected by Compton scattering of photons from the thorium-232 and radium-226 decay series.

Uncertainty Due to Interferences

Interference uncertainties are associated with gamma rays from other radionuclides that have energies similar to those of interest. The RTRAK uses low-resolution detectors which cannot differentiate between gammas of similar energy. To determine the net counts from the analyte of interest, these interfering counts must be subtracted from the total number of counts in the region of interest; this contributes to the overall uncertainty of the net analyte counts. Gamma rays from thorium-232 and radium-226 daughters can interfere with both the analyte counts and the background portion of the uranium-238 region of the spectrum (refer to Section 3.3).

Uncertainty Due to Peak Heights

Uncertainty due to gross peak counts is simply that uncertainty attributable to all of the counts observed for a gamma photon peak at the energy of interest.

4.1.1.2 System Uncertainty and Other Measurement Uncertainty

System and other measurement uncertainties comprise non-counting errors such as those related to system electronics and calibration errors. Because the RTRAK is a mobile detector system, precision will also encompass uncertainties related to the GPS system and operational variability (e.g., speed, vertical motion, etc.) inherent in the moving RTRAK system.

4.1.1.3 Heterogeneity

Although heterogeneity of the analytes in a study areas is important with regard to data interpretation, it is not included in this discussion as a contributor to the RTRAK measurement uncertainty. The effects of heterogeneity are analogous to the effects of non-representative sampling design on the results of a set of discrete samples collected from an area. Representative sampling is important when a limited number of samples is being used to represent the concentration of analytes throughout the entire area of interest. However, in practice, the RTRAK covers 100 percent of the area of interest, so there are no unmonitored locations that need to be represented by other measurements. While heterogeneity might make it difficult to exactly replicate each individual measurement obtained during a large area scan, the full set of measurements would be representative of the overall distribution of contamination. As is described in User Guidelines, Measurement Strategies, and Operational Factors for Deployment of In-situ Gamma Spectrometry at the Fernald Site, 20701-RP-0006, Revision A, the RTRAK is being used as a screening instrument to provide full coverage of a study area, and the results of single measurements will not be used alone. The result of a single measurement may indicate the possible presence of a hot spot or a WAC exceedance, but HPGe measurements will then be made to confirm the activity concentration and to delineate the area of exceedance. Consequently, it is not necessary to be able to precisely replicate either the activity concentration or location of any single measurement..

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4.1.2 Repeated Profile Measurements

The data from the repeated profile measurements (single tracks in the USID area and the Drum Baling Area; an elliptical track in the South Field) were evaluated to provide an indication of the overall measurement precision of the RTRAK system. The profile paths were divided into areas or segments of approximately equal size. The segment sizes were selected to minimize the contribution of spatial variations in radionuclide concentrations (i.e., to minimize heterogeneity) to the calculated standard deviations for the data within the segments. The assumption is that measurement points closest to one another should vary least in concentration, so that the variability seen in measured and calculated data within an area of limited size should be primarily a result of the precision of the measurement system. As demonstrated in this report, the assumption is valid for the USID area, but not for portions of the South Field or Drum Baling Areas. The standard deviations for the set of data within each segment represent the precision associated with the individual measurements.

USID Area

The profile for the USID area is a straight-line path that traverses locations of elevated activity (for the USID area) and a gravel-covered road. The profile was divided into 12 segments, including one encompassing the road. The segments at either end of the path were adjusted to exclude points in the segments where the RTRAK was turned at the end of each pass; 20 passes were made over this profile. The segments for the USID area are shown schematically in Figures 4-1A and 4-1B.

South Field Area

The profile located in the South Field area was an elliptical shape, and ten repeat RTRAK runs around this elliptical profile were made. This profile was divided into 50 segments. These segments are smaller in size than those for the USID and Drum Baling areas because the elliptical path is longer than the straight-line path and because a high degree of variability was observed in the data within a number of the larger segments that had originally been selected. A review of the individual measurements within those segments revealed that one or more measurements were significantly higher or lower than the others. These higher or lower measurements were considered an indication of actual variations in the radionuclide soil concentrations rather than indications of measurement error. To remove the impact of these variations, the segment sizes were reduced so that each segment would typically have only one or two measurements for each pass of the RTRAK (10-20 total measurements per segment). The segments selected for the South Field area are shown in Figures 4-2A and 4-2B. It can be seen by inspection of Figure 4-2B, that two of the segments (A-35 and A-36) along the profile path for the 1 mph/4 sec runs have only a few measurements. The 0.5 mph/8 sec runs also have only a few measurements in these segments. This results from many measurements having to be discarded due to GPS signal errors (see Appendix A). Trees and terrain in the South Field partially obstructed the satellite signal near segments A-35 and A-36 during the 0.5 mph/8-second runs. The 2 mph/2-second run was conducted at a time when the satellite position was favorable, so measurements were not affected by this problem. Therefore, the 2 mph/2sec run has a full complement of measurements.

Drum Baling Area

The profile for the Drum Baling Area is also a straight-line path. This profile was divided into 10 segments. The locations of the profile segments were adjusted to exclude the portion of the path where the RTRAK was turned at the end of a pass. A total of 20 passes was made over the profile. The profile segments are shown schematically in Figures 2-4, 2-5, and 2-6.

The energy spectra for the individual measurements made in each area were processed to provide the following data:

1. Total activity (gross counts per second) in the spectrum with no energy differentiation;
2. Activity concentrations for uranium-238, thorium-232, and radium-226;
3. Total system uncertainty for individual results;
4. Uncertainty for the individual results, based on counting uncertainty; and
5. Minimum detectable concentration (MDC) for the individual measurements, based on the counting uncertainty.

The individual results of the measurements within each segment were combined to calculate a mean concentration, the standard deviation of the distribution (i.e., the error associated with each individual measurement in the segment), average counting uncertainty, and the average minimum detectable concentration. The standard deviation of the distribution provides a measure of the total system precision expected for individual measurements within the area. The precision of the individual measurements is an important consideration in evaluating the usability of RTRAK data in potential applications.

4.1.3 Uranium-238

4.1.3.1 Overview of Repeated Profile Data

The uranium-238 measurements display the lowest degree of precision of the three radionuclides of interest which limits the usability of the data at low concentrations. The low degree of precision (high uncertainty) occurs because of the high spectrum background and because of interferences from thorium-232 and radium-226 measurements. The uranium-238 region of interest (943.1 - 1058.9 keV) is at the lowest energy region of interest of the three radionuclides, and at that low energy, the spectrum background under the uranium-238 peak is relatively high because of the high Compton continuum and the detector's inability to resolve naturally occurring gamma rays of comparable energies. The measured number of net uranium counts within the region of interest also contribute to the uranium-238 uncertainty, but at low uranium-238 concentrations, the uncertainty is dominated by the spectrum background with lesser but still significant contributions from the thorium-232 and radium-226 interferences.

The uranium-238 means, standard deviations, and percent standard deviations (standard deviation as a percentage of the mean) for each of the segments in the repeated profile measurements for the study areas are presented in Appendix C. The data can be found in Table C-1, and in Figures C-1 through C-3 for the USID Area, Table C-2 and Figures C-4 through C-6 for the South Field, and Table C-3 and Figures C-7 through C-9 for the Drum Baling Area. The data in Tables C-1 through C-3 are presented as a function of RTRAK operating speed and data acquisition time and are summarized in Table 4-1. Included in Table 4-1 are delta factors for each parameter. These are calculated by dividing the largest positive value of a parameter for any segment by the smallest positive value. The delta factors represent the range of the data. It can be seen by inspection of the tables and the figures that the means of the profile segments vary moderately for the USID Area and widely for the South Field, but the standard deviations do not vary as much. For example, for the USID Area at 2 second/ 2 mph, the mean concentration is 16.7 pCi/g and the delta factor is approximately 3.4. By comparison the delta factor for the standard deviation is only about 1.4. In the South Field area at 2 second/2 mph, the delta factor is 25.9 for the mean but only 2.3 for the standard deviation. Unlike the other areas, both the segment means and standard deviations in the Drum Baling Area display significant variability. At 2 second/2 mph, the delta factor for the Drum Baling Area means is approximately 5.1 and the delta factor for the standard deviations is approximately 4.0. The delta factor for the mean is larger than that of the USID Area, but smaller than that of the South Field, while for the standard deviations, the delta factor in the Drum Baling Area is larger than for either of the other two study areas. This suggests that the Drum Baling Area is more heterogeneous on a small scale basis than either the USID Area or the South Field.

4.1.3.2 Uranium-238 Precision

There is an overall apparent correlation between the mean and the uncertainty (standard deviation) in the study areas. Low concentration areas such as the USID and South Field areas have lower uncertainties. Higher concentration areas, such as the Drum Baling Area, have higher uncertainties. In the low concentration areas (USID Area and the South Field), the lack of correlation between mean and uncertainty is primarily a consequence of the low uranium-238 concentrations observed. At these concentrations, the standard deviation is primarily dependent on the magnitude of the Compton continuum and the thorium-232 and radium-226 uncertainties. At low concentrations, the net counts associated with the uranium-238 are small with respect to the spectrum background so they do not contribute significantly to the overall standard deviation. In the USID Area, the thorium-232 and radium-226 concentrations are low and relatively constant, so the Compton contribution is relatively constant across all of the profile segments. Consequently, the standard deviations remain relatively constant across all of the profile segments, regardless of the uranium-238 concentrations. The average standard deviations for the segments in the USID area are: 25.8 pCi/g for 2 second/2 mph, 26.7 pCi/g for 2 second/0.5 mph, and 14.1 pCi/g for 8 second/0.5 mph. The lower average standard deviation for the 8 second/0.5 mph measurements is a direct consequence of the longer data acquisition time. The standard deviation related to counting uncertainty, for a single measurement, is proportional to the square root of the count rate for that measurement and is inversely proportional to the square root of the counting time:

$$\sigma=\sqrt{\frac{R}{T}} \qquad (1)$$

where:

σ is the standard deviation associated with the count rate
R is the count rate (cps)
T is the count time

Consequently, for an increase in the acquisition time from two to eight seconds, the counting uncertainty would decrease by a factor of two. The standard deviation for the USID data for the 8 second acquisition time is approximately one-half that of the 2 second data (14.1 vs. 25.8 and 26.7). This is an indication that the counting uncertainty dominates the overall precision of the measurement at low uranium concentrations. The average counting uncertainty for the individual measurements in the USID Area is 11 pCi/g for the 8 second/ 0.5 mph combination of operating parameters. This is approximately 78% of the measured standard deviations of the measurements within the segments, which further supports the conclusion that the counting uncertainty dominates the measurement variability at low concentrations.

In the South Field, the uranium-238 standard deviations show more variability than in the USID Area (a factor of 2.3 for low to high vs. a factor of 1.4 for low to high for the 2 second/2 mph runs). This appears to be a consequence of the wider range of thorium-232 and radium-226 concentrations; the highest uranium-238 standard deviations are seen for measurement locations where the thorium and radium results are the highest. The radium and thorium concentrations affect the uranium-238 results because they both have gamma rays that can interfere with the gamma ray used to quantify the uranium. However, the average standard deviations for the various acquisition times are still similar to those of the USID Area, and there is again no apparent relationship between the mean of the measurements within a segment and the standard deviation. The average standard deviations are: 27.3 pCi/g for 2 second/2 mph, 20.2 pCi/g for 4 second/1 mph, and 14.3 pCi/g for 8 second/0.5 mph. The standard deviation for the 8 second data acquisition time is approximately half of that for the two second acquisition time as predicted by Equation 1. The average counting uncertainty for the eight second acquisition time is approximately 11 pCi/g which is approximately 77% of the overall average standard deviation. These results are consistent with that observed for the USID Area and indicate that the background counting uncertainty dominates the standard deviation.

The uranium concentrations within the DBA segments are significantly higher than for the other locations; by factors of approximately 20 and 12 for the South Field and the USID areas, respectively. Mean concentrations exceed 300 pCi/g for some segments. The highest uranium-238 concentrations are in segments DB-A01, DB-A02, DB-A04 and DB-A05. The maximum standard deviations for the individual segments were 200, 175, and 179 pCi/g , respectively, for the 2, 4, and 8 sec acquisition times. Average standard deviations for the segments are 90.14, 87.83 and 69.83 for the 2, 4, and 8 second acquisition times, respectively. These are higher than those observed for the USID and South Field areas, but this is partly reflective of 1) the higher concentrations of analytes present which result

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in a higher counting uncertainty and 2) heterogeneity within the DBA. Table 4-1 indicates that the percent standard deviations are significantly smaller in the DBA than those observed for the USID and South Field areas; this reflects the fact that the instrument error remains relatively constant regardless of the analyte concentration, and the relative counting uncertainty decreases with increased concentration. The heterogeneity of the uranium-238 in the soil is greater for the DBA than the other two areas and this contributes to the overall uncertainty, but this contribution is smaller than the increase in the uranium-238 concentration. As with the other two areas, there is no apparent correlation between the segment means and the standard deviations. This may be a consequence of the analyte heterogeneity.

One important observation that can be clearly seen by inspecting Table 4-1 is that the standard deviations for the uranium-238 measurements in the USID Area and the South Field are generally larger than the segment means, with average percent standard deviations ranging from 171 to 474 %. The minimum standard deviation that can be expected for a single uranium-238 measurement is approximately 26 pCi/g for 2 second acquisition times and 14 pCi/g for 8 second acquisition times. Such large standard deviations preclude the use of individual RTRAK measurements at low concentrations. At higher uranium-238 concentrations, the background counting uncertainty will be a smaller fraction of the result, and the individual measurements can provide useable data. The actual concentration levels at which the individual RTRAK measurements could be used reliably depend on the precision requirements for using the data. For illustration purposes, it will be assumed that data for which the upper 95% confidence interval is less than 50%of the measurement value would be acceptable for use. Individual measurements would meet this criterion for uranium-238 concentrations of 102 pCi/g (306 ppm for total uranium) for 2 second acquisition times and 55 pCi/g (165 ppm for total uranium) for 8 second acquisition times.

4.1.3.3 Summary of Uranium-238 Results

The conclusions supported by the data may be summarized as follows:

1. The dominant contributor to the uranium-238 standard deviation at low concentrations is the counting uncertainty associated with the spectrum background.

2. The standard deviations of the measurements change by a factor approximately proportional to the inverse square root of a change in the acquisition time. Precision can be improved by increasing the acquisition time. If the acquisition time is increased

by a factor of four, the precision increases (standard deviation decreases) by a factor of two.

3. The presence of elevated concentrations of thorium-232 or radium-226 increases the standard deviations of uranium-238 measurements.

4. The poor precision limits the use of individual measurements at low uranium-238 concentrations. For individual measurements an upper 95% confidence interval of less than 50% of the reported concentration would be seen for uranium-238 concentrations greater than 55 pCi/g (165 ppm) for 8 second data acquisition times and 102 pCi/g (306 ppm) for 2 second data acquisition times.

5. High concentration uranium areas also have high uncertainties, reflecting large counting errors associated with peaks in the uranium-238 region of interest. However, the percent standard deviations are significantly smaller than in low concentration areas, reflecting the fact that instrument error remains constant regardless of analyte concentration, and the relative counting uncertainty decreases with increased concentration.

4.1.4 Thorium-232

4.1.4.1 Overview of Repeated Profile Data

The thorium measurements have the lowest standard deviations of the three isotopes measured, irrespective of speed and data acquisition time. This is to be expected because there are fewer gamma rays of significant abundance at higher energies that contribute to the Compton continuum at the thorium region of interest. Consequently, the spectrum background is much smaller than for either uranium-238 or radium-226. The thorium-232 means, standard deviations, and percent standard deviations are presented in Appendix C, Table C-4 and Figures C-10 through C-12 for the USID area, Table C-5 and Figures C-13 through C-15 for the South Field, and Table C-6 and Figures C-16 through C-18 for the Drum Baling Area. These data are summarized in Table 4-2.

Within the USID Area, the thorium-232 concentrations are low, with the mean of the profile segments near 0.75 pCi/g for all combinations of operating parameters and with delta factors for the means ranging from 1.58 to 2.48. This mean concentration is comparable to, or less than, expected natural background levels of thorium-232 in soils. The standard deviations are relatively constant, with delta factors ranging between 1.3 and 1.6. For most segments, the standard deviations for the measurements at the 8 second acquisition time are approximately a factor of two lower than for the 2 second measurements, as expected. The average counting uncertainty for the 8 second/0.5 mph measurements is 0.11 pCi/g, which is about 58 percent of the average overall standard deviation (0.19 pCi/g) for 8 second/0/5 mph measurements. In the South Field area, the variability of the standard deviations is larger, with delta factors of 3.6 for 2 second/2 mph, 6.4 for 4 second/1 mph, and 5.6 for 8 second/0.5 mph. The average segment mean thorium-232 concentration (approximately 3.8 pCi/g) across the DBA profile is approximately a factor of four higher than those observed for the other two study areas. For the individual segments, the highest observed concentrations in the DBA are 6.35, 7.98, and 6.83 pCi/g, respectively, for the 2, 4, and 8 sec acquisition times. These maxima were observed for segment DB-A09. Segment DB-A10 had comparable concentrations of approximately 6 pCi/g for all acquisition times. Across the segments, the concentrations varied significantly, with delta factors of approximately 3. The thorium-232 standard deviations for the DBA measurements are higher than those for the other two study areas, and the percent standard deviations are smaller than those observed for the other two areas. As was the case for the uranium-238, the larger standard deviations reflect the higher analyte concentrations and the heterogeneity of the thorium in the soil. Across the DBA, the average segment standard deviations are 1.10, 1.14, and 0.78 pCi/g for the 2, 4, and 8 sec acquisition times, respectively, and the corresponding delta factors 4.38, 6.11, and 3.93. The percent standard deviations are approximately 29, 28, and 21 percent for 2, 4, and 8 sec acquisition times, respectively, with delta factors of 2.1, 2.1, and 2.7.

4.1.4.2 Thorium-232 Precision

As noted above, the thorium-232 measurements have the lowest standard deviations of the three analytes of interest. A large portion of the uncertainty is from the counting uncertainty. As an example, the average counting uncertainty for the 8 second/0.5 mph measurements in the South Field is 0.12 pCi/g, which is 54% of the overall average standard deviation of 0.22 pCi/g for the segments. For measurements where the spectrum backgrounds are low, as they are for the spectral region used to quantify thorium-232, it would be expected that there would not be significant contributions from other sources. Where the background is high, the counting uncertainty will tend to dominate the uncertainty.

As can be seen from Table 4-2, the standard deviations as a percentage of the mean are still quite high at the low concentrations observed in the three study areas, ranging from a low of 26% for the 8 second acquisition time to a high of 49% for the 2 second acquisition times. This limits the useability of the data from individual measurements at concentrations near background. Conversely, at high thorium concentration areas, the standard deviations as a percentage of the mean are lower (20 to 30%), and individual measurements in high concentration areas are not limited by the precision. The actual concentration levels at which the individual RTRAK measurements could be used reliably would be dependent upon the precision requirements for use of the data.

4.1.4.3 Summary of Thorium-232 Results

The conclusions supported by the data may be summarized as follows:

1. The counting uncertainty remains a significant contributor to the overall standard deviation, but other factors can contribute approximately half of the total uncertainty for eight second acquisition times.
2. Precision can be improved by increasing the acquisition time. The improvement will be approximately equal to the ratio of inverse square roots of the acquisition times.
3. The precision limits the use of individual measurements at thorium-232 concentrations near background.

4.1.5 Radium-226

4.1.5.1 Overview of Repeated Profile Data

The radium-226 means, standard deviations, and percent standard deviations are presented in Table C-7 and Figures C-19 through C-21 for the USID Area, in Table C-8 and Figures C-22 through C-24 for the South Field, and in Table C-9 and Figures C-25 through C-27 for the Drum Baling Area. These data are summarized in Table 4-3. The radium standard deviations are smaller than those for uranium, but larger than those for thorium-232. The radium-226 region of interest (1699.3 - 1850.9 keV) is at a higher energy than the uranium region of interest, and therefore, the magnitude of the Compton continuum is smaller than for uranium. For the typical FEMP spectrum, the predominant gamma rays of significant abundance that contribute to the Compton continuum at this energy are from daughters of thorium-232. The net effect is a much lower background for radium-226 than for uranium-238. The major counting-uncertainty contributions to the radium-226 standard deviation are the Compton continuum and the net radium-226 counts, but the thorium-232 daughter gamma rays can cause interferences when the thorium-232 activities are elevated.

Within the USID Area, the radium-226 concentrations are low, with the means of the profile segments about 0.8 pCi/g. The average standard deviations for the 2 second acquisition-time measurements are also approximately 0.8 pCi/g, with a delta factors of about 1.4. For the 8 second acquisition-time measurements, the mean is 0.8 pCi/g and the average standard deviation 0.4 with a delta factor of 1.3.

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In the South Field Area, the variability of the standard deviations is larger than in the USID area, with delta factors ranging between 8.4 and 14.

4.1.5.2 Radium-226 Precision

At low concentrations, the background counting uncertainty is the major contributor to the overall standard deviation of the measurements. As an example, within the USID Area, the average standard deviation for the 8 second acquisition-time measurements is approximately a factor of two lower than for the 2 second acquisition time measurements. The average counting uncertainty for the 8 second/0.5 mph measurements is 0.3 pCi/g, which is 75% of the average overall uncertainty (0.40 pCi/g).

The highest standard deviations in the South Field are found in segments with either high radium-226 or high thorium-232. For the high thorium-232 segments, the dominate source of uncertainty is the Compton continuum within the radium region of interest. In segments where the radium-226 is high, the Compton continuum is still a significant source, but the uncertainty associated with the net radium counts also contributes significantly. For many of the segments, the ratios of the average standard deviations vary as the ratios of the square root of the inverse of the data acquisition time. However, there are a number of cases where this is not the case. For segments where either the radium-226 or thorium-232 results are high, the standard deviation does not consistently decrease with increased acquisition time by the expected factor. The reason is not clear, but it may be a consequence of variability (heterogeneity) in the radium-226 or thorium-232 concentrations in the study area. The concentrations appear to vary rapidly over a small area, so it may be that a small change in the positioning of the RTRAK in the repeated passes could lead to a large change in the activity within the field of view. This would lead to a larger standard deviation than would be expected simply from the counting uncertainty. This is the case for both the average standard deviations of all of the segments, and the individual segments. The average counting uncertainty for the 8 second/0.5 mph measurements is 0.4 pCi/g. This is comparable to the average overall standard deviation of the segments, but is significantly lower than the maximum value of 1.7 pCi/g. This supports the conclusion that factors other than counting uncertainty are contributing to the high standard deviations.

The radium-226 standard deviations for the DBA measurements are much larger than those observed for the other two study areas, although the percent standard deviations are lower. The elevated standard deviation for radium-226 reflects both the heterogeneity of the radium-226 in the DBA and higher radium-226 concentrations. The average profile standard deviations are 3.21, 2.68. And 2.44 pCi/g with delta factors of 4.6, 4.8, and 6.7, respectively, for 2, 4, and 8 sec acquisition times. The percent standard deviations are approximately 49, 38, and 35 percent with delta factors of 4.7, 3.1, and 4.4, respectively, for the 2, 4, and 8 sec acquisition times.

As can be seen from Table 4-3, the standard deviations as a percentage of the mean are very high at the low concentrations observed in the study areas, ranging from a low of 35 percent for the 8 second acquisition time in the Drum Baling Area to a high of 102 percent for the 2 second acquisition time in the USID Area. The minimum standard deviation that can be expected is approximately 0.8 pCi/g for 2 second acquisition times and 0.4 pCi/g for 8 second acquisition times. The actual concentration levels at which the individual RTRAK measurements could be used reliably would be dependent upon the precision requirements for use of the data.

4.1.5.3 Summary of Radium-226 Results

The conclusions supported by the data may be summarized as follows:

1. The counting uncertainty is a major contributor to the overall standard deviation, accounting for approximately 75% of the overall standard deviation.
2. Precision can be improved by increasing the acquisition time, by a factor approximately equal to the square root of the increase.

4.1.6 Total Activity

4.1.6.1 Overview of Repeated Profile Data

Total activity (gross counts per second) results are obtained from the RTRAK by simply summing all of the counts seen in the RTRAK gamma spectrum and dividing by the data acquisition time. This includes all counts from the Compton continuum as well as counts from all gammas that interact with the detector, regardless of the radionuclide. Consequently, there are no contributions to the uncertainty of the results that are comparable to spectrum background or interferences. The counting uncertainty is simply given by the square root of the total number of counts accumulated during the acquisition period. Because of the large number of counts accumulated in even a 2 second measurement in an area of low activity concentrations (frequently of the order of 10,000 counts), the fractional counting uncertainty is small, typically around 1 percent. The overall standard deviation is a combination of this small counting uncertainty plus other measurement uncertainties.

The means, standard deviations, and percent standard deviations for the total activity data are presented in Table C-10 and Figures C-28 through C-30 for the USID Area, in Table C-11 and Figures C-31 through C-33 for the South Field, and in Table C-12 and Figures C-34 through C-36 for the Drum Baling Area. These data are summarized in Table 4-4. The delta factors for the segment means in all three study areas are small, ranging from 1.2 in the USID Area to 3.1 in the South Field and delta factors for the standard deviations range from as low as 7.7 for 2 second acquisition time in the USID Area to as high as 45 for the 8 second acquisition time measurements in the South Field.

4.1.6.2 Total Activity Precision

The total activity measurements show the most consistent segment means across the three combinations of parameters and have a much smaller percent standard deviation than the isotopic data. This is to be expected because the large number of counts obtained in a single measurement results in a low counting uncertainty. For the isotopic measurements, the counting uncertainties are all high at low concentrations. The smallest average percent standard deviation for the isotopic data is for thorium in the Drum Baling Area, at approximately 21% for an 8 second measurement. However, for total activity, the average percent standard deviation is about 6% for any of the acquisition times evaluated, in both the USID Area and in the South Field. In the Drum Baling Area, the percent standard deviations average about 14%. The standard deviations for the individual measurements are also comparable for the three combinations of speed/time in all three areas. This occurs despite the fact that the acquisition times range over a factor of four. It would generally be expected that the measurements with the longer acquisition times would consistently have smaller standard deviations because, as explained previously, the counting uncertainty is proportional to the square root of the acquisition time. Consequently, when acquisition times differ by a factor of four, the uncertainties should differ by a factor of two. The fact that this is not observed is an indication that other sources of measurement uncertainty or the variability in the actual soil activity concentration are significant contributors to the overall standard deviation of the total activity data. It is interesting to note that the highest percent standard deviations in the USID Area are observed for the road and for Areas 7 and 8. The high standard deviation for the road is in part because of the lower activity concentration at that location; the lower the activity, the fewer counts and the higher the counting uncertainty. Areas 7 and 8 are on either side of the road. Some of the measurements assigned to these areas overlap the edges of the road. This results in several measurements that have a much lower activity concentration than the other points within the areas, which increases the overall standard deviation of the data set.

Within the South Field, the highest percent standard deviations are typically in areas which have the highest radium or thorium activities. This may be an indication that the high concentrations of these nuclides are localized into very small areas and variations in the positioning of the RTRAK on the multiple passes result in significant differences in the activity concentrations within the RTRAK field of view.

The average gross counts per second for the segment means across the full DBA profile are more than a factor of 5 larger than those for the other study areas. This is consistent with the higher concentrations observed for the uranium-238, thorium-232, and radium-226. The average segment means are 15666, 15796, and 15703 cps with delta factors of 2.6. 2.6, and 2.5, respectively, for 2, 4, and 8 sec acquisition times. Four of the individual segments have total activity which are approximately a factor of two higher than the others: DB-A01, DB-A02, DB-A04, and DB-A05. These are the same segments that have elevated concentrations of uranium-238 and radium-226. The segment with the lowest total activity is DB-A07; this segment has the lowest concentrations of uranium-238 and thorium-232 and a lower than average radium-226 concentration. The total activity results are consistent with the analyte-specific data previously discussed in this report.

For the total activity, it is difficult to estimate the minimum expected standard deviation from the average standard deviations of the segments, because there are indications that inhomogeneity in radionuclide concentrations may be a significant contributor to the overall standard deviation. Standard deviations near 2% are common for many of the segments, and it appears that this is most likely the minimum standard deviation that can be expected. With such good precision, individual total activity measurements can be useable to provide general indications of elevated activity. Because total activity measurements provide no radionuclide-specific information it's use is limited to general radiological screening.

4.1.6.3 Summary of Total Activity Results

The conclusions supported by the repeated profile measurements may be summarized as follows:

1. Total activity measurements exhibit a high degree of precision.

2. The counting uncertainty does not appear to be the major contributor to the overall standard deviation.

3. Total activity measurements do not provide radionuclide-specific information.

4. Total activity measurements can be effective in defining general patterns of elevated activity.

4.2 ACCURACY

4.2.1 Initial Calibration Assessment

As discussed in Section 3.3, the RTRAK's initial calibration was obtained by developing calibration equations based upon regression analyses of static RTRAK data and HPGe measurements. To assess the validity of the calibration, static RTRAK measurements and HPGe measurements were made at four locations in the USID area. The results of these measurements and their calculated standard deviations are shown in Table 4-5. The RTRAK values are the means of a series of measurements taken at each location. RTRAK measurements were taken for both 2 second (150 measurements) and 8 second (38 measurements) acquisition times for a total of 300 seconds of data acquisition. The HPGe measurements are single measurements at each of the same locations at 900 seconds. The standard deviations shown on the table are the standard deviations of the mean for the RTRAK measurements and the counting standard deviation for the HPGe data.

The data exhibit excellent agreement for the uranium-238 and thorium-232 results. The radium-226 agreement was not as good. Based upon these data, the uranium and thorium calibrations remain valid, but the radium calibration yields RTRAK data consistently 20% to 30% higher than HPGe data. One explanation for the radium disagreement may be that the measurements were conducted on different days, approximately one week apart. Possibly a change in soil moisture and other environmental conditions caused a change in the rate that radon emanated from the soil; this would result in different degrees of equilibrium of the radium decay products which are the sources of gamma rays used to quantify radium. The effect of radon disequilibrium on in-situ radium-226 gamma measurements is discussed in the User's Manual (DOE 1998a).

4.2.2 Comparison of HPGe and Dynamic RTRAK Isotopic Results

Table 4-6 compares HPGe values averaged over the entire USID Area with RTRAK values averaged over the same area. As the table indicates, there is good agreement between the two systems for radium and thorium when their data are averaged over the whole area, with a slightly high bias present in the RTRAK. The agreement for uranium is not as good for the 2 second/2 mph run, but becomes markedly better for the 8 second/0.5 mph run.

Table 4-7 compares in-situ HPGe results with RTRAK isotopic values averaged over each of the individual HPGe viewing areas (36 in all) in the USID area for each of the three principal gamma-emitting isotopes: radium-226, thorium-232 and total uranium. Again, agreement between average RTRAK measurements with individual HPGe measurements is generally good for the 8 second/0.5 mph runs for all three isotopes, but a number of significant disagreements between data points occur for the 2 second/2 mph runs. This latter disagreement is probably a consequence of the low concentrations and poor RTRAK precision at those low concentrations.

4.2.3 Extended Range Calibration Assessment

A full area scan of a portion the Drum Baling Area was performed and the results processed using the extended range calibration. Table 4-8 compares the average of the in-situ HPGe measurements over the full area of the scan with average RTRAK measurements covering the same area. The large standard deviations for the measurements demonstrates the high degree of analyte heterogeneity within the Drum Baling Area. Particularly in light of such heterogeneity, the agreement between the HPGe and RTRAK measurements is exceptional. The RTRAK measurements agree with HPGe within 20 percent for all analytes and both sets of operating conditions except for thorium-232 at 0.5 mph/8sec; HPGe and RTRAK differ by approximately 23 percent for the 8-second acquisition times. This agreement indicates that the extended range calibration provides satisfactory agreement between HPGe and RTRAK.

4.3 TOTAL UNCERTAINTY OF RTRAK MEASUREMENTS

One of the critical quality parameters for any measurement is its overall uncertainty. The overall uncertainty is a combination of random and systematic uncertainties. The studies described in Section 4.1 were designed to determine the random uncertainty affecting the RTRAK results by measuring the standard deviations of a series of measurements over the same locations. The USID and South Field areas have relatively homogeneous patterns of contamination, so the observed uncertainties for measurements in these study areas represent random sources of uncertainty related to the operation of the RTRAK system and the statistics of radioactive decay. The Drum Baling Area clearly has heterogeneous radionuclide concentrations, so the standard deviations measured there reflect the variability in the analyte distributions in addition to uncertainties normally associated with RTRAK system measurements. For the purposes of this discussion, the random sources will be divided into two components, counting uncertainty and instrument uncertainty. The instrument uncertainty is that associated with instabilities in the electronics and variables related to maintaining the operating speed and direction of the RTRAK. The instrument uncertainty can be assumed to be relatively constant for a given set of operating conditions, regardless of the activity concentration. The counting uncertainty will vary with the number of counts in the peak and background regions of interest.

The relationship between the observed uncertainty, the counting uncertainty and the instrument uncertainty is given by the relationship.

$$\sigma^2_{\text{random}} = \sigma^2_{\text{counting}} + \sigma^2_{\text{instrument}} \qquad (2)$$

where:

σ^2_{random} =	The squared uncertainty of a set of RTRAK measurements, from random sources.
$\sigma^2_{\text{counting}}$ =	The squared counting uncertainty. This is obtained by applying standard propagation of error relationships to the uncertainties associated with the raw counting data.
$\sigma^2_{\text{instrument}}$ =	The squared uncertainty or variance associated with instrument parameters. These were calculated from the repeated profile data discussed in this report.

The data from the USID and South Field areas (Tables 4-1, 4-2,and 4-3) were used to estimate the instrument uncertainties so that total uncertainty estimates could be made for various analyte concentrations. The average observed uncertainties were determined for each analyte for each of the sets of operating conditions evaluated. These are shown in Table 4-9 in the column labeled σ_{observed}. For each profile segment, the average counting uncertainty was calculated by applying standard propagation of uncertainty relationships to the raw counting data; this is shown in Table 4-9 as σ_{counting}. Because the observed uncertainties represent random uncertainties, Equation 2 can be used with them and the counting uncertainties to calculate the instrument uncertainty, which is shown in Table 4-9 as $\sigma_{\text{instrument}}$. Table 4-9 effectively summarizes the results of the repeated profile measurements. The instrument uncertainty can now be used for calculating expected uncertainties for other analyte concentrations.

A complete assessment of the uncertainty of a measurement must include systematic uncertainties.

The total uncertainty of a measurement is given by the relationship (ANSI N42.14-1991):

$$U^2_{TOT} = \sigma^2_{random} + 1/3(\Sigma(\delta_{systematic})^2) \qquad (3)$$

where:

U_{TOT} = The total uncertainty of the measurement, including the sources of maximum estimated systematic uncertainties and random uncertainties.

σ_{random} = The standard deviations of random sources of uncertainty

$\delta_{systematic}$ = The estimated maximum systematic uncertainties

The primary source of systematic uncertainty considered in this evaluation is the calibration uncertainty. The RTRAK is calibrated by performing a regression analysis on co-located static RTRAK measurements and HPGe measurements. The calibrations and associated uncertainty are discussed in Section 3 and Appendix A. The calibration uncertainties are divided into two components: the uncertainty related to the regression fit and the uncertainty related to the agreement between the HPGe measurements and laboratory analyses. In the July 1997 report entitled "Comparability of In-Situ Gamma Spectrometry and Laboratory Data" and the October 1997 report "Comparability of In-Situ Gamma Spectrometry and Laboratory Measurements of Radium-226 (Addendum #2)", it was shown that in-situ HPGe measurements and laboratory results agree within 20%. Consequently, a value of 20% of the RTRAK measurement is used as an estimate of the systematic uncertainty associated with the comparability of in-situ measurements with laboratory results. This uncertainty is shown in Tables 4-10a, b, and c in the column labeled $\delta_{comparability}$. The systematic uncertainties of the calibration equations are defined by multiplying the measured concentration by the averages of the absolute values of the fractional residuals from the regression analysis. This is discussed in Section 3.3. The fractional residuals are: 0.09 for thorium-232, 0.15 for radium-226 and 0.24 for uranium-238. This portion of the calibration uncertainty is shown in Tables 4-10 a, b, and c in the column labeled $\delta_{regression}$.

The counting uncertainty for a specific isotope measurement is a function of both the number of counts that are related to unscattered gamma rays detected and to the number of counts that contribute to the gamma photon spectrum background and interferences. Thus, the counting uncertainty for any specific isotope is dependent upon the concentrations of the isotope in question along with the concentrations of any other gamma emitting isotopes that are present. In practice, this means that it is not possible to make a highly accurate ***a priori*** estimate of the counting uncertainty for an analyte at a given concentration. The counting uncertainty can only be determined *a posteriori* or it can be estimated by making assumptions of the concentrations at which other interfering analytes are present, as is done below.

Tables 4-10a, b, and c present the contributions to the uncertainty of RTRAK measurements and the estimated total uncertainties (standard deviations) for analyte concentrations near the FRL, hot spot criteria, and WAC (uranium-238 only) for 2, 4, and 8 sec acquisition times. For uranium-238, values are provided for FRLs equal to 10, 20, and 82 ppm. Equations 2 and 3 were combined and used to calculate the total uncertainty. The following assumptions were made for these calculations:

1. Gamma photon spectrum background at the FRL and at hot spot limits that is unrelated to the presence of other gamma emitting nuclides is constant and is taken from the spectrum backgrounds measured in the USID area.

2. Instrument-related uncertainties ($\sigma_{instrument}$) were obtained from the repeated profile measurements described in this report.

3. For measurements near the FRLs, it is assumed that the concentrations of analytes that interfere with other analytes (i.e., thorium-232 and radium-226 interfering with uranium-238) or contribute to their background are equal in concentration to their corresponding FRL.

4. For measurements near the hot spot criterion (3xFRL) it is assumed that the concentrations of analytes that interfere with other analytes or contribute to their background, are equal in concentration to their corresponding FRL.

5. At WAC concentrations of uranium-238, it is assumed that the uranium-238 counting uncertainty is equivalent to the average percent counting uncertainty observed for measurements within the DBA that are at or greater than the WAC. This takes into consideration elevated radium and thorium concentrations that may be present.

The information included in Tables 4-10a, b and c is important in using RTRAK to determine whether an action limit has been exceeded. The total uncertainty provides the basis for establishing confidence intervals, determining how data are to be displayed, when and in what manner data should be combined, and defining detection limits. The systematic uncertainties and total uncertainties are used in subsequent sections of this report to calculate minimum detectable concentrations and trigger levels.

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4.4 SPATIAL AVERAGING AND AGGREGATION OF MEASUREMENTS

The variability present in RTRAK measurements for a specific isotope from a given area is a combination of measurement error and the spatial heterogeneity for that isotope in a given area. The results presented in Section 4.0 clearly demonstrate that increasing the counting time can significantly decrease the standard deviation of the individual measurements. Because the counting uncertainty is the primary source of uncertainty for uranium-238 and radium-226 at low concentrations, the standard deviations for uranium and radium should decrease by the square root of the factor of any increase in acquisition time. In fact, data from the repeated profile measurements showed that the standard deviations of uranium-238 and radium-226 were reduced by approximately a factor of two by increasing the acquisition time from two to eight seconds. A significant improvement was also realized for thorium, although it was not as large.

Another means of reducing the effect of the measurement standard deviation is to spatially average or aggregate RTRAK measurements over a larger area than the individual measurements and then to determine the standard deviation of the means of those larger areas. Aggregation of measurements over an area has a "smoothing" effect by averaging out variability. The larger the averaging area, the greater the "smoothing" effect will be. Thus, increasing averaging area sizes reduces the uncertainty associated with a concentration value, but also reduces the spatial resolution of the measurements by averaging the data over a larger area of spatial variability. The latter effect is not necessarily desirable because it limits the ability to identify small localized areas of contamination. Whether this is a problem or not depends on the intended use of RTRAK data. For example, if the objective is to determine during data collection for pre-certification whether a certification unit is likely to pass or fail the actual certification process, a spatially averaged RTRAK result that may cover an area as large as an acre in extent and include more than 1,000 RTRAK data points may be utilized. On the other hand, if the objective is to locate hot spots, spatial averaging must be minimized.

The standard deviation of the mean of an aggregation measurement is an inverse function of the square root of the number of values contributing to the spatial average. For example, the resulting average from four RTRAK measurement points will have only half of the standard deviation of the individual points contributing to the average. If nine measurements points are included in the average, the resulting average will have only one third the measurement error of the individual points. In the case of a 2 second acquisition time collected at 2 mph and a 4 second acquisition time collected at 1 mph, the viewing window of the RTRAK is approximately 8.8 m^2 (94.7 ft^2). Because the viewing window extends beyond the physical footprint of the RTRAK, sequential RTRAK measurements overlap. For a given acquisition time, the slower the speed, the greater the overlap of viewing windows. In the case of data collected at 2 mph with a 2 second acquisition time, averaging 10 sequential measurements results in a read area of 47.4 m^2 (510 ft^2), which is approximately 5 times as great as the read area for an individual measurement. Figure 4-4 shows the relationship between relative standard deviation of the mean and the number of points contributing to a spatial average for the 2 second acquisition time, 2 mph case.

The issue with spatial averages is how large an averaging area is required to reduce the standard deviation to acceptable levels. As indicated in Section 2.2.2.1, 100% of the USID area was characterized by the RTRAK at three different combinations of tractor speed and data acquisition time. One objective of carrying out such detailed coverage was to delineate the effects of spatially averaging measurements over areas of varying size.

In the discussion below, the mean and standard deviation associated with individual measurements of all two-second and eight-second measurements times are presented under the "Raw Data" heading in Table 4-11. The approximately one-acre portion of the USID area was subdivided into circular areas having 10, 15, 20, 30, and 40 feet areas. The mean of all two second and eight second measurement points falling within those areas was computed. Then the grand mean and the standard deviation of the grand mean were calculated for each size circular area. The results of these calculations are also shown in Table 4-11.

Table 4-11 and Figures 4-5 through 4-7 show how the data variability decreases as averaging area sizes are increased for the 2 mph/2 sec acquisition time runs and the 0.5 mph/8 sec acquisition time runs. The effects of increasing the averaging radius or aggregating measurements are as noted above; when the averaging radius is increased by a factor of two (i.e., the area increases by a factor of four), the standard deviation of the mean decreases by a factor of two.

As shown in Table 4-11, the size of the averaging area that is required to reduce measurement error is isotope-specific. For example, RTRAK thorium-232 measurements have significantly less measurement error than RTRAK radium-226 measurements, and consequently RTRAK thorium-232 spatial averages require a smaller averaging window than radium-226 averages to attain small standard deviations. Table 4-12 illustrates this concept for thorium-232, radium-226 and total uranium at concentrations equal to their FRL and three times their FRL assuming measurement errors associated with individual measurements using a 2 second acquisition time at 2 mph. Here, for the purposes of illustration, acceptable error has been defined as a standard deviation or standard deviation of the mean that is less than 10% of the FRL for concentrations at the FRL, or less than 10% of three times the FRL for concentrations that are three times the FRL.

Spatial averages can be constructed in a variety of ways. The most straightforward are block averages, where a region of interest that has been surveyed with the RTRAK is broken into blocks, and an average RTRAK value is assigned to each block based on the RTRAK points contained within that block. The disadvantage of this approach is that all detail within each block is lost, which can be a significant handicap if blocks are large. The approach used in this document makes use of moving window averages. This approach defines a grid over the region of interest, and then for each grid node calculates an average using all of the points within a specified distance from the node. The advantages of this approach are that the result has the same spatial resolution as provided by the grid and that each grid node can be assigned multiple averages, i.e., one for a window radius of 5 feet, one for 10 feet, etc. The disadvantage of this approach is that it tends to be more computationally intensive than a straight block average. There are more sophisticated averaging techniques, such as point or block kriging. With data as dense and regular as the RTRAK data, however, they provide little benefit in exchange for significantly greater computational burdens.

4.5 MINIMUM DETECTABLE CONCENTRATION

MDC refers to the statistically determined quantity of a radionuclide that can be measured at a preselected confidence level. The MDC is the *a priori* activity concentration that a specific instrument and technique can be expected to detect 95% of the time. When stating the detection capability of an instrument, this value should be used. The MDC is the detection limit L_D, multiplied by an appropriate conversion factor to give units of activity concentration (Marssim 1997). The magnitude of the MDC is a function of instrument parameters, radiological background levels, and the measurement procedure.

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The concept of using the L_D for measurements of radionuclides was first proposed by L. Currie in 1968. It is intended to be an *a priori* (before the first) estimate of the activity level that a system or technique can reliably measure under a given set of conditions. **The L_D is not intended to be used *a posteriori* (after the fact) to evaluate individual measurements.**

L. Currie defines the detection limit L_D as:

$$L_D = 2ks, \qquad (4)$$

where:

k = factor related to the acceptable risk for false detection and false non- detection, assuming that risk level is equal. At a 5% risk, k = 1.645

s = the standard deviation of the measurement when the net measurement is near the background

For this study, the detection limit was calculated in units of activity concentration (pCi/g), and thus is referred to as the MDC.

The repeat profile runs in the USID area were used as the basis of calculating the MDC. The repeated profile runs were located so that the profile would cross a road in the USID study area. The road has been graded and covered with gravel, so that the road surface can be considered relatively uncontaminated. For the purpose of the RTRAK applicability study, the multiple measurements in the area encompassing the road are assumed to be representative of background. The standard deviations of the distribution are equivalent to the standard deviation of the individual measurements. These standard deviations were combined with the systematic uncertainties to calculate the total uncertainty for the measurements. The total uncertainty was used to calculate *a priori* MDCs for the three combinations of acquisition time and travel speed. Because the combination of 4 sec/1 mph was not run in the USID area, the MDC was estimated from the 8-second data. The acceptable risk for both false detection and false non-detection was set at 5%, as stated above, so k = 1.645, and the MDC = 3.29s. The *a priori* MDCs are presented in Table 4-13. The lowest MDCs for all three isotopes are obtained for the 8 second acquisition time. However, even at 8 seconds, the MDC for uranium-238 (47 pCi/g) significantly exceeds the FRL for total uranium (47 pCi/g uranium-238 equates to 141 ppm of total uranium). For all three acquisition times, only the thorium-232 MDC does not exceed its FRL.

As shown in Table 4-13, increasing the acquisition time decreases the MDC for uranium-238 and radium-226. If the only contribution to the uncertainty were the counting uncertainty, the MDC would decrease by the square root of the factor by which the acquisition time has changed. That would indicate that increasing the acquisition time from 2 to 8 seconds would decrease the MDC by a factor of two. The fact that the observed decrease for uranium-238 and radium-226 was only about a factor of 1.3 to 1.5 for those nuclides indicates that other factors contribute to the uncertainty. One key factor may relate to the precision by which the RTRAK operator was able to duplicate the path for all of the repeated runs.

A standard deviation of a distribution represents the precision associated with the individual measurements, or how well each measurement is likely to estimate the mean of the distribution. However, a mean calculated from multiple measurements is a much better estimate of the true mean. The standard deviation of the mean, also called the standard error, is the measure of the precision of that calculated mean. The standard error is obtained by dividing the standard deviation of the distribution by the square root of the number of measurements used in calculating the mean, or $s/(n)^{1/2}$. Because the MDC is a function of the standard deviation, an MDC associated with a mean calculated from multiple measurements would be based on the standard error. Consequently, results calculated by aggregating multiple measurements would have a lower MDC, although that would be gained at the expense of poorer spatial resolution. The effects of aggregating or spatially averaging RTRAK measurements is discussed in detail in Section 5.5.2.

The greater the number of measurements that are aggregated to establish the mean concentration, the smaller are the standard error and the MDC. The number of measurements that should be aggregated is dependent upon the required MDC and spatial resolution. MDCs obtained by aggregating 5, 10, 50, and 100 measurements for the 8 seconds/0.5 mph run are shown in Table 4-14. The MDCs obtained for the individual measurements shown in Table 4-13 are also presented in Table 4-14 for comparison. The MDCs for uranium can be reduced to below the FRL (equivalent to 27 pCi/g of uranium-238) with the aggregation of as few as five measurements. The MDCs for radium-226 and thorium-232 are below the FRLs for individual measurements at the 8-second acquisition time, but aggregating clearly lowers their MDCs further.

4.6 TRIGGER LEVELS

To facilitate use of the RTRAK results, “trigger levels" can be established to aid in decision making. A "trigger level" can be defined as an analyte concentration that, if exceeded by a field or laboratory measurement, provides the basis for some subsequent action to be taken. The general approach described in this report can be applied to any data set, but the tables provided are specific to the RTRAK configuration as used at the FEMP. In practice, a trigger level would be associated with a regulatory limit or internal action limit. The advantage of using a trigger level is that it provides a single value against which data can be quickly compared to screen a location for potential exceedances of a given limiting criterion.

Because every RTRAK measurement will have some corresponding uncertainty, trigger levels are typically set below the actual limiting criteria to provide confidence that a regulatory or operational limit will not be exceeded, The difference between the limiting criterion and the trigger level is a function of the precision of the actual measurement value being used and the required level of confidence that a measurement at or below the trigger level will not exceed the limiting criterion. Because the precision of a measurement is analyte specific, the trigger level will also be analyte specific.

The use of aggregate measurements complicates establishing a trigger level; consequently, a practical approach to setting a trigger level is to arbitrarily define a minimum acceptable trigger level as a percentage of the applicable regulatory limit. This percentage must be a value such that the trigger level is well above the detection limit and is also well above the radionuclide background concentration in soils. Equation 5, below, can then be solved for the corresponding number of measurements that must be aggregated in order for the standard deviation to be acceptably reduced.

$$\text{Minimum Acceptable Trigger} = L - k\sigma_{\text{limit}}/(n)^{1/2} \qquad (5)$$

where:

$L =$ the magnitude of the limiting criterion such as the FRL, hot spot criterion, or WAC

$k =$ the standard normal variate, a statistical factor related to the acceptable confidence level of the measurement. At the 95% confidence level, k is equal to 1.645 for a single-tailed distribution.

$\sigma_{\text{limit}} =$ the standard deviation assumed for RTRAK measurements of soil concentrations numerically equal to the limit

$n =$ the number of measurements that are aggregated

For the purposes of this discussion, the minimum acceptable RTRAK trigger level is set at 70% of the applicable regulatory limit. This is not based on a rigorous statistical or quantitative evaluation, but was chosen in part because at 70% of the limit, acceptable trigger levels can be achieved by aggregating only two measurements for uranium WAC exceedances. In addition, the Real-Time Working Group concluded that a trigger level lower than 750 ppm would be acceptable for the uranium WAC; 70% of the WAC is 721 ppm.

The trigger levels and the number of measurements that must be aggregated (calculated using Equation 5 and the uncertainties estimated for individual RTRAK measurement in Tables 4-10a, 4-10b, and 4-10c) to achieve these levels are presented in Tables 4-15 through 4-17. Table 4-15 is for total uranium at FRLs of 10, 20, and 82 ppm respectively. Tables 4-16 and 4-17 are for thorium-232 and radium-226, respectively. Each table lists trigger levels for the FRL and WAC (total uranium only) at acquisition times of 2, 4, and 8 seconds.

The tables can be interpreted as follows:

1. The first and second columns define the applicable limiting criterion.
2. The third column is the minimum acceptable trigger level calculated as 70% of the limiting criterion.
3. Subsequent columns provide trigger level information for the three acquisition times.
4. The following information is provided for each acquisition time:
    a. The column labeled "Single Measurement Trigger" shows the trigger level that would be calculated for a single measurement. The column is annotated to indicate whether this satisfies the requirement to exceed the minimum acceptable trigger level. The notation "marginal" indicates that the single measurement trigger level is less than 10% lower than the minimum acceptable trigger level.
    b. The column labeled "No. Aggregated Measurements (Trigger)" shows the number of measurements that must be aggregated in order to reduce the uncertainty to achieve the minimum acceptable trigger level. This number is calculated using Equation 5 and rounded up to the next whole measurement. Underneath the number of measurements, in parentheses, is the actual calculated trigger level that would be obtained for the aggregated measurements.

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Care must be taken when aggregating RTRAK measurements to ascertain that the area represented by the aggregated measurements is not significantly larger than the hot spot of interest. This can be a practical limitation to the use of RTRAK to detect hot spots. Section 4.3-1 of the User's Manual (DOE 1998a) provides a method for determining the approximate size of an area represented by a number of aggregated measurements.

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TABLE 4-1
SUMMARY OF U-238 INFORMATION
FOR USID, SOUTH FIELD, AND DRUM BALING AREAS

Operating Conditions	Area	Isotope	Avg. Segment Means (pCi/g)	Delta Factor for Segment Means	Avg. Segment SDs (pCi/g)	Delta Factor for Segment SDs	Avg. Segment % SDs	Delta Factor for Segment % SDs
2 mph/2 sec	USID	U-238	16.73	3.38	25.82	1.35	171.11	3.08
0.5 mph/2 sec	USID	U-238	14.38	3.88	26.66	1.38	217.22	3.84
0.5 mph/8 sec	USID	U-238	17.16	2.59	14.10	1.28	87.65	2.69
2 mph/2 sec	SF	U-238	9.88	25.90	27.28	2.32	474.14	18.96
1 mph/4 sec	SF	U-238	10.57	11.23	20.19	2.78	277.88	26.37
0.5 mph/8 sec	SF	U-238	9.71	14.23	14.29	3.84	285.78	131.7
2 mph/2 sec	DBA	U-238	203.33	5.08	90.14	3.95	52.88	2.8
1 mph/4 sec	DBA	U-238	206.12	5.03	87.83	4.82	47.08	3.08
0.5 mph/8 sec	DBA	U-238	209.04	5.08	69.83	6.85	38.28	5.65

TABLE 4-2
SUMMARY OF THORIUM-232 INFORMATION FOR USID, SOUTH FIELD, AND DRUM BALING AREAS

Operating Conditions	Area	Isotope	Avg. Segment Means (pCi/g)	Delta Factor for Segment Means	Avg. Segment SDs (pCi/g)	Delta Factor for Segment SDs	Avg. Segment % SDs	Delta Factor for Segment % SDs
2 mph/2 sec	USID	Th-232	0.75	2.48	0.35	1.31	48.88	2.32
0.5 mph/2 sec	USID	Th-232	0.74	1.91	0.36	1.29	49.58	1.97
0.5 mph/8 sec	USID	Th-232	0.75	1.58	0.19	1.56	25.95	2.23
2 mph/2 sec	SF	Th-232	0.82	5.62	0.39	3.62	49.54	2.40
1 mph/4 sec	SF	Th-232	0.86	8.54	0.30	6.42	37.58	4.27
0.5 mph/8 sec	SF	Th-232	0.83	5.31	0.22	5.55	26.13	3.16
2 mph/2 sec	DBA	Th-232	3.76	3.25	1.10	4.38	29.38	2.08
1 mph/4 sec	DBA	Th-232	3.89	3.61	1.14	6.11	28.33	2.11
0.5 mph/8 sec	DBA	Th-232	3.83	2.82	0.78	3.93	20.55	2.72

TABLE 4-3
SUMMARY OF RADIUM-226 INFORMATION
FOR USID, SOUTH FIELD, AND DRUM BALING AREAS

Operating Conditions	Area	Isotope	Avg. Segment Means (pCi/g)	Delta Factor for Segment Means	Avg. Segment SDs (pCi/g)	Delta Factor for Segment SDs	Avg. Segment % SDs	Delta Factor for Segment % SDs
2 mph/2 sec	USID	Ra-226	0.77	1.57	0.77	1.40	100.43	1.24
0.5 mph/2 sec	USID	Ra-226	0.79	1.52	0.8	1.37	101.65	1.35
0.5 mph/8 sec	USID	Ra-226	0.81	1.24	0.40	1.33	50.16	1.60
2 mph/2 sec	SF	Ra-226	1.36	9.43	0.91	2.75	82.08	6.63
1 mph/4 sec	SF	Ra-226	1.39	8.40	0.67	5.54	57.39	11.04
0.5 mph/8 sec	SF	Ra-226	1.38	13.79	0.47	7.17	40.84	14.2
2 mph/2 sec	DBA	Ra-226	8.68	8.32	3.21	4.62	49.44	4.66
1 mph/4 sec	DBA	Ra-226	8.38	7.06	2.68	4.77	38.28	3.13
0.5 mph/8 sec	DBA	Ra-226	8.46	8.89	2.44	6.70	35.31	4.39

TABLE 4-4
SUMMARY OF GROSS COUNTS INFORMATION FOR USID, SOUTH FIELD, AND DRUM BALING AREAS

Operating Conditions	Area	Isotope	Avg. Segment Means (cps)	Delta Factor for Segment Means	Avg. Segment SDs (cps)	Delta Factor for Segment SDs	Avg. Segment % SDs	Delta Factor for Segment % SDs
2 mph/2 sec	USID	Gross Counts	2937	1.53	142	7.73	5.30	10.91
0.5 mph/2 sec	USID	Gross Counts	2924	1.15	152	8.16	5.78	11.98
0.5 mph/8 sec	USID	Gross Counts	2456	1.39	176	10.75	6.36	13.84
2 mph/2 sec	SF	Gross Counts	2849	2.95	198	23.52	6.29	14.36
1 mph/4 sec	SF	Gross Counts	2893	3.07	194	37.57	5.90	22.6
0.5 mph/8 sec	SF	Gross Counts	2883	2.93	180	45.13	5.34	21.78
2 mph/2 sec	DBA	Gross Counts	15666	2.60	2147	9.41	13.31	4.97
1 mph/4 sec	DBA	Gross Counts	15796	2.59	2420	8.88	15.02	4.97
0.5 mph/8 sec	DBA	Gross Counts	15703	2.47	2298	11.83	14.48	6.47

TABLE 4-5
COMPARISON OF CO-LOCATED STATIC RTRAK AND HPGe MEASUREMENTS

Data Point	Data Acquisition Time	Uranium-238 (pCi/g)				Thorium-232 (pCi/g)				Radium-226 (pCi/g)			
		HPGe	HPGe Std Dev	RTRAK	RTRAK SD of Mean	HPGe	HPGe Std Dev	RTRAK	RTRAK SD of Mean	HPGe	HPGe Std Dev	RTRAK	RTRAK SD of Mean
10	2 sec	22.5	0.57	20.46	2.30	0.7	0.02	0.84	0.03	0.7	0.02	0.87	0.08
10	8 sec	22.5	0.54	22.16	2.45	0.7	0.02	0.82	0.02	0.7	0.02	0.93	0.06
15	2 sec	22.4	0.58	20.77	2.20	0.8	0.02	0.89	0.03	0.7	0.02	0.91	0.07
15	8 sec	22.4	0.58	23.60	2.44	0.8	0.02	0.86	0.03	0.7	0.02	1.06	0.06
35	2 sec	13.4	0.54	10.65	2.19	0.8	0.03	0.80	0.03	0.7	0.02	0.87	0.06
35	8 sec	13.4	0.54	11.98	2.26	0.8	0.03	0.81	0.02	0.7	0.02	0.87	0.07
41	2 sec	13.3	0.54	11.74	2.18	0.7	0.02	0.80	0.03	0.7	0.02	0.95	0.07
41	8 sec	13.3	0.54	15.76	2.20	0.7	0.02	0.77	0.03	0.7	0.02	0.78	0.07

TABLE 4-6
COMPARISON OF AVERAGE RTRAK RESULTS WITH HPGe RESULTS - USID AREA

	Radium-226 (pCi/g)			Thorium-232 (pCi/g)			Total Uranium (ppm)		
	HPGe	2 mph/ 2 sec	0.5 mph/ 8 sec	HPGe	2 mph/ 2 sec	0.5 mph/ 8 sec	HPGe	2 mph/ 2 sec	0.5 mph/ 8 sec
Average	0.68	0.76	0.78	0.72	0.75	0.72	50	37	52
Std Dev	0.06	0.18	0.09	0.11	0.10	0.09	12	21	14

TABLE 4-7
COMPARISON OF HPGe AND THE AVERAGE OF RTRAK MEASUREMENTS WITHIN THE HPGe FIELD OF VIEW

		Radium-226 (pCi/g)			Thorium-232 (pCi/g)			Total Uranium (ppm)		
HPGe ID	CPS	HPGe	RTRAK 2 mph 2 sec acq	RTRAK 0.5 mph 8 sec acq	HPGe	RTRAK 2 mph 2 sec acq	RTRAK 0.5 mph 8 sec acq	HPGe	RTRAK 2 mph 2 sec acq	RTRAK 0.5 mph 8 sec acq
500349-10	3036	0.67	1.00	0.66	0.73	0.70	0.76	67.46	77.73	54.30
500349-11	2809	0.67	0.80	0.70	0.69	0.74	0.76	45.83	36.09	32.01
500349-12	2639	0.73	0.80	0.82	0.75	0.70	0.60	46.48	5.61	58.50
500349-13	2367	0.49	0.68	0.78	0.31	0.55	0.49	14.47	8.22	25.32
500349-14	2591	0.61	0.61	0.76	0.67	0.60	0.59	53.65	37.53	53.34
500349-15	2982	0.76	0.63	0.72	0.84	0.69	0.83	76.41	62.91	65.04
500349-16	2990	0.66	0.78	0.72	0.79	0.84	0.78	52.16	46.23	57.66
500349-17	2924	0.66	0.40	0.72	0.75	0.72	0.79	41.09	17.46	34.86
500349-18	3139	0.74	0.42	0.81	0.80	0.91	0.80	55.71	52.20	61.71
500349-19	3107	0.71	0.87	0.87	0.77	0.78	0.73	56.66	36.90	64.44
500349-20	2637	0.75	0.78	0.75	0.74	0.66	0.74	59.02	53.25	36.51
500349-21	2423	0.50	0.56	0.87	0.31	0.62	0.62	14.66	10.20	45.54
500349-22	2829	0.70	0.76	0.79	0.84	0.75	0.64	54.55	44.31	66.00
500349-23	3003	0.68	0.93	0.78	0.77	0.80	0.75	47.93	44.13	70.68
500349-24	3078	0.68	0.77	0.58	0.75	0.72	0.76	46.15	40.62	55.86
500349-25	3108	0.66	1.04	0.74	0.78	0.90	0.82	44.64	16.35	40.50
500349-26	3132	0.74	1.00	0.85	0.76	0.89	0.75	52.46	27.51	54.96
500349-27	3154	0.72	0.85	0.87	0.77	0.89	0.81	54.85	52.71	60.57

TABLE 4-7
(continued)

HPGe ID	CPS	Radium-226 (pCi/g) HPGe	Radium-226 (pCi/g) RTRAK 2 mph 2 sec acq	Radium-226 (pCi/g) RTRAK 0.5 mph 8 sec acq	Thorium-232 (pCi/g) HPGe	Thorium-232 (pCi/g) RTRAK 2 mph 2 sec acq	Thorium-232 (pCi/g) RTRAK 0.5 mph 8 sec acq	Total Uranium (ppm) HPGe	Total Uranium (ppm) RTRAK 2 mph 2 sec acq	Total Uranium (ppm) RTRAK 0.5 mph 8 sec acq
500349-28	3115	0.72	0.92	0.85	0.75	0.82	0.80	57.24	72.30	53.67
500349-29	2863	0.75	0.46	0.85	0.72	0.70	0.52	50.09	10.41	48.63
500349-30	2555	0.68	0.88	0.75	0.67	0.55	0.76	47.40	39.60	32.67
500349-31	3113	0.64	0.74	0.78	0.76	0.78	0.74	49.46	50.10	40.53
500349-32	3074	0.70	0.61	0.84	0.76	0.88	0.81	52.14	18.39	47.25
500349-33	3024	0.67	0.72	0.70	0.70	0.79	0.67	52.77	11.37	47.73
500349-34	2908	0.69	0.59	0.87	0.67	0.85	0.72	47.96	6.99	63.93
500349-35	2989	0.73	0.67	0.70	0.75	0.85	0.77	40.14	6.66	38.13
500349-36	3067	0.70	0.95	0.75	0.71	0.93	0.84	44.98	21.57	61.77
500349-37	3074	0.73	0.91	0.81	0.74	0.70	0.70	49.44	75.03	35.49
500349-38	2985	0.72	0.66	0.74	0.68	0.81	0.57	47.68	28.98	49.02
500349-39	2962	0.68	1.14	0.66	0.76	0.84	0.57	51.51	53.01	49.98
500349-40	2840	0.68	0.60	0.95	0.73	0.68	0.89	50.65	47.70	68.22
500349-41	3052	0.69	0.86	0.89	0.70	0.70	0.73	39.84	61.02	50.85
500349-6	2815	0.63	0.91	0.77	0.66	0.58	0.70	41.98	27.39	36.24
500349-7	2945	0.67	0.85	0.99	0.78	0.74	0.79	69.48	61.95	75.96
500349-8	2612	0.67	0.37	0.66	0.70	0.71	0.62	59.64	18.84	48.69
500349-9	3040	0.63	0.83	0.85	0.68	0.79	0.76	64.17	60.75	87.51

TABLE 4-8
COMPARISON OF AVERAGE RTRAK RESULTS WITH HPGe RESULTS - DRUM BALING AREA

	Radium-226 (pCi/g)			Thorium-232 (pCi/g)			Total Uranium (ppm)		
	HPGe	2 mph/ 2 sec	0.5 mph/ 8 sec	HPGe	2 mph/ 2 sec	0.5 mph/ 8 sec	HPGe	2 mph/ 2 sec	0.5 mph/ 8 sec
Average	5.6	5.3	6.3	2.6	2.4	3.2	744	633	741
Std Dev	4.2	4.5	5.4	2.2	2.1	4.6	468	537	582

TABLE 4-9
CONTRIBUTIONS TO OBSERVED STANDARD DEVIATIONS (pCi/g)

	$\sigma_{observed}$*	$\sigma_{counting}$	$\sigma_{instrument}$
8 seconds			
Uranium-238	14	11	9
Thorium-232	0.22	0.11	0.19
Radium-226	0.40	0.32	0.24
4 Seconds			
Uranium-238	20	16	12
Thorium-232	0.3	0.17	0.25
Radium-226	0.65	0.52	0.39
2 Seconds			
Uranium-238	26	22	14
Thorium-232	0.35	0.23	0.27
Radium-226	0.80	0.71	0.37

* $\sigma_{observed}$ is taken from Tables 4-1, 4-2, and 4-3; column 6 (average segment SDs, pCi/g).

TABLE 4-10a
ESTIMATED CONTRIBUTORS TO ANALYTE STANDARD DEVIATIONS

ACQUISITION TIME	LIMIT TYPE	URANIUM-238 (ppm)					
		LIMIT ppm	$\sigma_{INSTRUMENT}$	$\sigma_{COUNTING}$	$\delta_{REGRESSION}$	$\delta_{COMPARABILITY}$	U_{TOTAL}
2 SEC	FRL	82	42	70	20	16	83
2 SEC	FRL=82 HOT SPOT (3x)	246	42	75	59	49	97
2 SEC	FRL=82 HOT SPOT (2x)	164	42	73	39	33	89
2 SEC	U FRL=10 ppm	10	42	68	2	2	80
2 SEC	FRL=10 HOT SPOT (3x)	30	42	68	7	6	80
2 SEC	FRL=10 HOT SPOT (2x)	20	42	68	5	4	80
2 SEC	U FRL=20 ppm	20	42	68	5	4	80
2 SEC	FRL=20 HOT SPOT (3x)	60	42	69	14	12	82
2 SEC	FRL=20 HOT SPOT (2x)	40	42	69	10	8	81
2 SEC	WAC	1030	42	199	247	206	275
4 SEC	FRL	82	36	50	20	16	64
4 SEC	FRL=82 HOT SPOT (3x)	246	36	54	59	49	79
4 SEC	FRL=82 HOT SPOT (2x)	164	36	52	39	33	70
4 SEC	U FRL=10 ppm	10	36	49	2	2	61
4 SEC	FRL=10 HOT SPOT (3x)	30	36	49	7	6	61
4 SEC	FRL=10 HOT SPOT (2x)	20	36	49	5	4	61
4 SEC	U FRL=20 ppm	20	36	49	5	4	61
4 SEC	FRL=20 HOT SPOT (3x)	60	36	50	14	12	62
4 SEC	FRL=20 HOT SPOT (2x)	40	36	49	10	8	62
4 SEC	WAC	1030	36	143	247	206	237
8 SEC	FRL.	82	27	36	20	16	47
8 SEC	FRL=82 HOT SPOT (3x)	246	27	38	59	49	64
8 SEC	FRL=82 HOT SPOT (2x)	164	27	37	39	33	54
8 SEC	U FRL=10 ppm	10	27	34	2	2	43
8 SEC	FRL=10 HOT SPOT (3x)	30	27	35	7	6	44
8 SEC	FRL=10 HOT SPOT (2x)	20	27	35	5	4	44
8 SEC	U FRL=20 ppm	20	27	35	5	4	44

TABLE 4-10a
(continued)

ACQUISITION TIME	LIMIT TYPE	URANIUM-238 (ppm)					
		LIMIT ppm	$\sigma_{INSTRUMENT}$	$\sigma_{COUNTING}$	$\delta_{REGRESSION}$	$\delta_{COMPARABILITY}$	U_{TOTAL}
8 SEC	FRL=20 HOT SPOT (3x)	60	27	35	14	12	46
8 SEC	FRL=20 HOT SPOT (2x)	40	27	35	10	8	45
8 SEC	WAC	1030	27	100	247	206	213

TABLE 4-10b
ESTIMATED CONTRIBUTORS TO ANALYTE STANDARD DEVIATIONS

		THORIUM-232 (pCi/g)					
ACQUISITION TIME	LIMIT TYPE	LIMIT (pCi/g)	$\sigma_{INSTRUMENT}$	$\sigma_{COUNTING}$	$\delta_{REGRESSION}$	$\delta_{COMPARABILITY}$	U_{TOTAL}
2 SEC	FRL	1.5	0.27	0.28	0.14	0.30	0.43
2 SEC	HOT SPOT (3x)	4.5	0.27	0.42	0.41	0.90	0.76
2 SEC	HOT SPOT (2x)	3.0	0.27	0.36	0.27	0.60	0.60
4 SEC	FRL	1.5	0.25	0.20	0.14	0.30	0.37
4 SEC	HOT SPOT (3x)	4.5	0.25	0.30	0.41	0.90	0.69
4 SEC	HOT SPOT (2x)	3.0	0.25	0.26	0.27	0.60	0.52
8 SEC	FRL	1.5	0.19	0.14	0.14	0.30	0.30
8 SEC	HOT SPOT (3x)	4.5	0.19	0.21	0.41	0.90	0.64
8 SEC	HOT SPOT (2x)	3.0	0.19	0.18	0.27	0.60	0.46

TABLE 4-10c
ESTIMATED CONTRIBUTORS TO ANALYTE STANDARD DEVIATIONS

		RADIUM-226 (pCi/g)					
ACQUISITION TIME	LIMIT TYPE	LIMIT (pCi/g)	$\sigma_{INSTRUMENT}$	$\sigma_{COUNTING}$	$\delta_{REGRESSION}$	$\delta_{COMPARABILITY}$	U_{TOTAL}
2 SEC	FRL	1.70	0.37	0.74	0.26	0.34	0.86
2 SEC	HOT SPOT (3x)	5.10	0.37	0.93	0.77	1.02	1.24
2 SEC	HOT SPOT (2x)	3.40	0.37	0.84	0.51	0.68	1.04
4 SEC	FRL	1.70	0.39	0.53	0.26	0.34	0.70
4 SEC	HOT SPOT (3x)	5.10	0.39	0.67	0.77	1.02	1.07
4 SEC	HOT SPOT (2x)	3.40	0.39	0.61	0.51	0.68	0.87
8 SEC	FRL	1.70	0.24	0.38	0.26	0.34	0.51
8 SEC	HOT SPOT (3x)	5.10	0.24	0.47	0.77	1.02	0.91
8 SEC	HOT SPOT (2x)	3.40	0.24	0.43	0.51	0.68	0.69

TABLE 4-11
EFFECT OF AGGREGATING MEASUREMENTS - USID AREA

2 mph/2 sec Acquisition Time

		Radium-226 (pCi/g)		Thorium-232 (pCi/g)		Total Uranium (ppm)	
	No.* Meas.	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Raw Data	1	0.76	0.88	0.75	0.37	37	79
10' Radius	7	0.77	0.41	0.75	0.22	37	48
15' Radius	15	0.77	0.31	0.75	0.18	37	33
20' Radius	26	0.76	0.23	0.75	0.14	37	25
30' Radius	60	0.76	0.15	0.74	0.11	36	18
40' Radius	106	0.76	0.11	0.74	0.09	36	13

0.5 mph/8 sec Acquisition Time

		Radium-226 (pCi/g)		Thorium-232 (pCi/g)		Total Uranium (ppm)	
	No.* Meas.	Mean	Std Dev	Mean	Std Dev	Mean	Std Dev
Raw Data	1	0.79	0.38	0.73	0.21	51	41
10' Radius	7	0.78	0.24	0.72	0.16	51	28
15' Radius	15	0.79	0.16	0.73	0.12	51	21
20' Radius	26	0.79	0.12	0.73	0.10	51	16
30' Radius	60	0.79	0.08	0.73	0.07	50	10
40' Radius	106	0.79	0.06	0.73	0.06	51	7

* The method of calculating the number of RTRAK measurements per area is explained in Section 4.3 of the User's Manual (DOE 1998a).

TABLE 4-12
NUMBER OF RTRAK POINTS REQUIRED FOR AVERAGING TO ATTAIN A PRE-SPECIFIED ERROR CRITERIA AT THE FRL AND THREE TIMES THE FRL

	Radium-226 (pCi/g)			Thorium-232 (pCi/g)			Total U (ppm)		
	Error* (pCi/g)	Averaging Radius (ft)	# of Points	Error* (pCi/g)	Averaging Radius (ft)	# of Points	Error* (ppm)	Averaging Radius (ft)	# of Points
FRL:	0.17	20	26	0.15	10	7	8	37	91
3xFRL	0.51	9	5	0.45	7	3	24	15	15

* Errors given are 10% of the FRL of 10% of 3x FRL

TABLE 4-13
A PRIORI MDC (pCi/g) BASED UPON MEASUREMENTS IN THE USID AREA

Nuclide	2 mph/2 sec	0.5 mph/2 sec	0.5 mph/8 sec	0.5 mph/4 sec
Uranium-238 (pCi/g)	73	70	47	57[a]
Thorium-232 (pCi/g)	1.4	1.3	1.4	1.4[a]
Radium-226 (pCi/g)	2.6	2.5	2.0	2.2[a]

[a] Estimated from data for 8-second acquisition time.

TABLE 4-14
A PRIORI MDC (pCi/g) BASED UPON TOTAL SYSTEM UNCERTAINTY FOR AGGREGATED MEASUREMENTS
(0.5 mph/8 sec)

	Number of Aggregated Measurements				
Nuclide	1[a]	5	10	50	100
Uranium (pCi/g)	47[b]	21	15	6.6	4.7
Thorium (pCi/g)	1.4	0.63	0.44	0.20	0.14
Radium (pCi/g)	2.0	0.89	0.63	0.28	0.20

[a] MDCs for one measurement are from Column 4 of Table 4-12.
[b] Numbers are MDCs in pCi/g

TABLE 4-15
TOTAL URANIUM RTRAK TRIGGER LEVELS

			2 sec Acquisition Time		4 sec Acquisition Time		8 sec Acquisition Time	
Application	**Limit (ppm)**	**Minimum Acceptable Trigger (ppm)**	**Single Measurement Trigger (ppm)**	**No. Aggregated Measurements (Trigger, ppm)**	**Single Measurement Trigger (ppm)**	**No. Aggregated Measurements (Trigger, ppm)**	**Single Measurement Trigger (ppm)**	**No. Aggregated Measurements (Trigger, ppm)**
FRL	10	7	-122 unacceptable	1925 (7)	-90 unacceptable	1113 (7)	-61 unacceptable	568 (7)
FRL	20	14	-111 unacceptable	480 (14)	-80 unacceptable	279 (14)	-52 unacceptable	146 (14)
FRL	82	57	-53 unacceptable	31 (58)	-21 unacceptable	18 (58)	7 unacceptable	10 (58)
WAC	1030	721	577 unacceptable	3 (768)	640 marginal	2 (754)	680 marginal	2 (783)

TABLE 4-16
THORIUM-232 RTRAK TRIGGER LEVELS IN pCi/g

			2 sec Acquisition Time		4 sec Acquisition Time		8 sec Acquisition Time	
Application	**Limit (pCi/g)**	**Minimum Acceptable Trigger (pCi/g)**	**Single Measurement Trigger (pCi/g)**	**No. Aggregated Measurements (Trigger, pCi/g)**	**Single Measurement Trigger (pCi/g)**	**No. Aggregated Measurements (Trigger, pCi/g)**	**Single Measurement Trigger (pCi/g)**	**No. Aggregated Measurements (Trigger, pCi/g)**
FRL	1.5	1.05	0.79 unacceptable	3 (1.09)	0.89 unacceptable	2 (1.07)	1.00 unacceptable	2 (1.15)
WAC	na	na	na	na	na	na	na	na

TABLE 4-17
RADIUM-226 RTRAK TRIGGER LEVELS IN pCi/g

			2 sec Acquisition Time		4 sec Acquisition Time		8 sec Acquisition Time	
Application	**Limit (pCi/g)**	**Minimum Acceptable Trigger (pCi/g)**	**Single Measurement Trigger (pCi/g)**	**No. Aggregated Measurements (Trigger, pCi/g)**	**Single Measurement Trigger (pCi/g)**	**No. Aggregated Measurements (Trigger, pCi/g)**	**Single Measurement Trigger (pCi/g)**	**No. Aggregated Measurements (Trigger, pCi/g)**
FRL	1.7	1.2	0.28 unacceptable	8 (1.20)	0.54 unacceptable	6 (1.23)	0.86 unacceptable	3 (1.21)
WAC	na	na	na	na	na	na	na	na

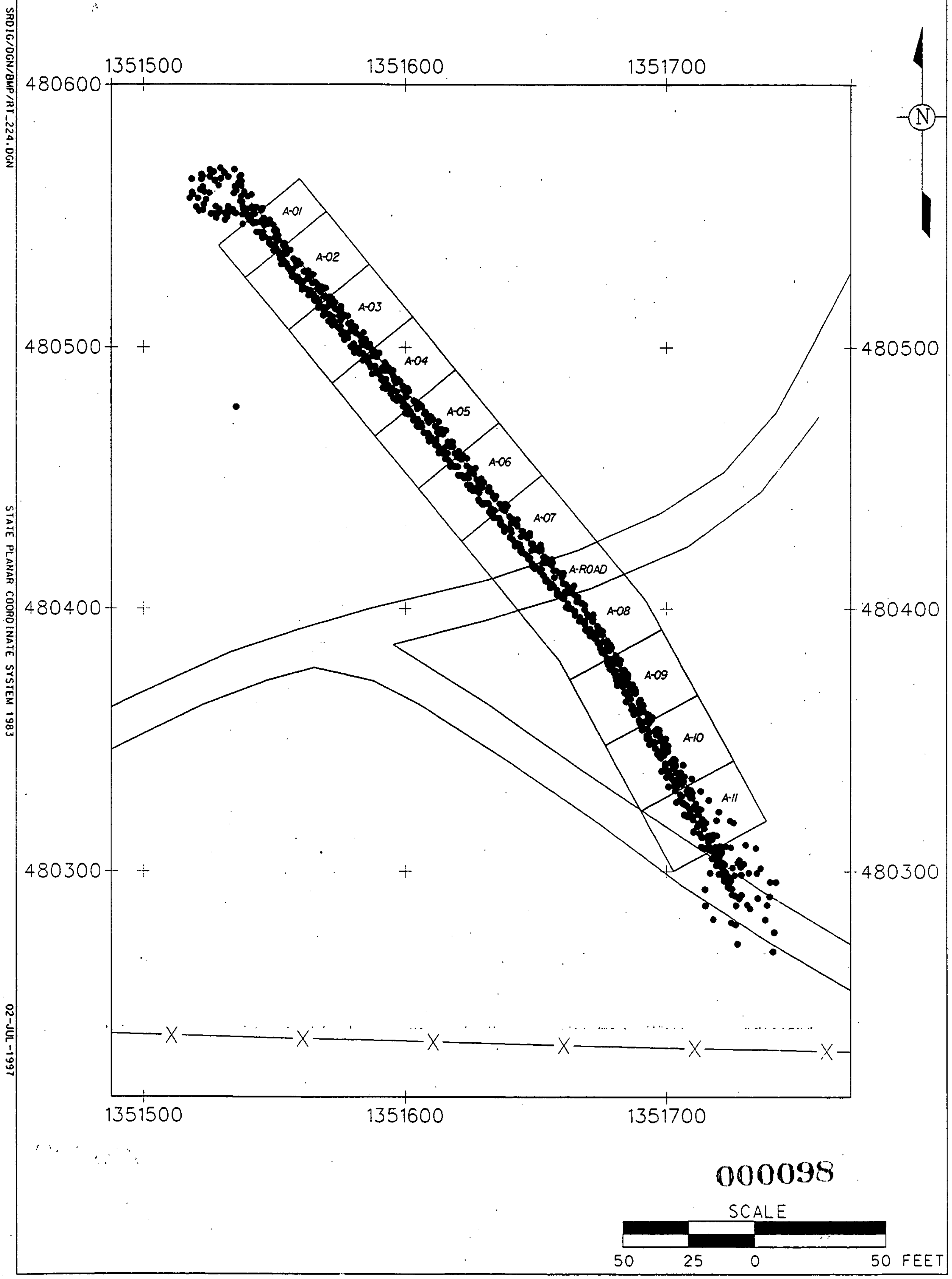

SRDIG/DGN/BMP/RT_224.DGN
STATE PLANAR COORDINATE SYSTEM 1983
02-JUL-1997
1351500
1351600
1351700
480600
480500
480400
480300
N
A-01
A-02
A-03
A-04
A-05
A-06
A-07
A-ROAD
A-08
A-09
A-10
A-11
SCALE
50
25
0
50 FEET

FIGURE 4-1A. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR U.S.I.D. AREA - 2 M.P.H. / 2 SEC. ACQUISITION

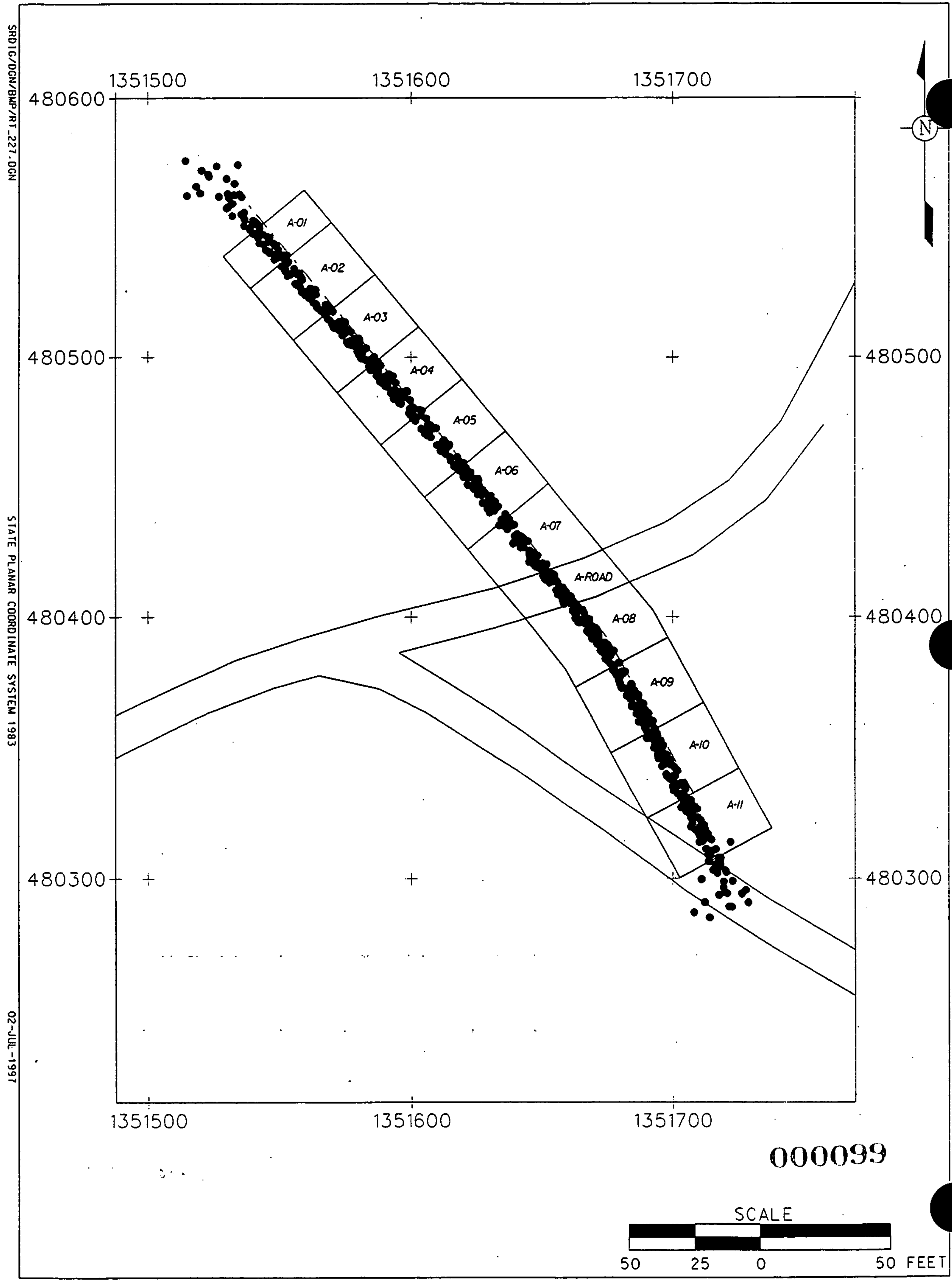

SRD1G/DGN/BMP/RT_227.DGN
STATE PLANAR COORDINATE SYSTEM 1983
02-JUL-1997
1351500
1351600
1351700
480600
480500
480400
480300
N
A-01
A-02
A-03
A-04
A-05
A-06
A-07
A-ROAD
A-08
A-09
A-10
A-11
SCALE
50
25
0
50 FEET

FIGURE 4-1B. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR U.S.I.D. AREA - 0.5 M.P.H. / 8 SEC. ACQUISITION

SRDIG/DGN/BMP/RT_240.DGN

STATE PLANAR COORDINATE SYSTEM 1983

7-JUL-1997

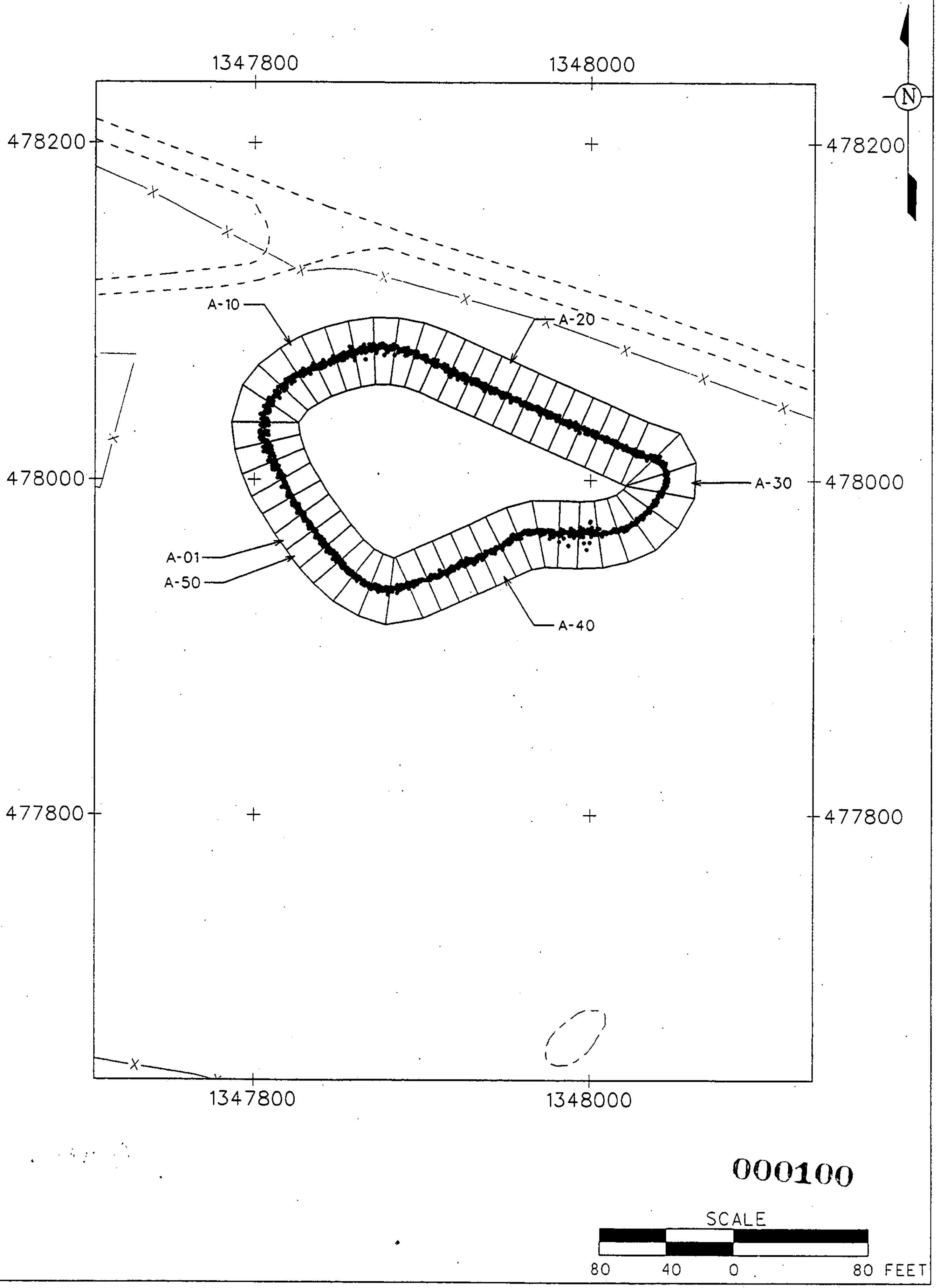
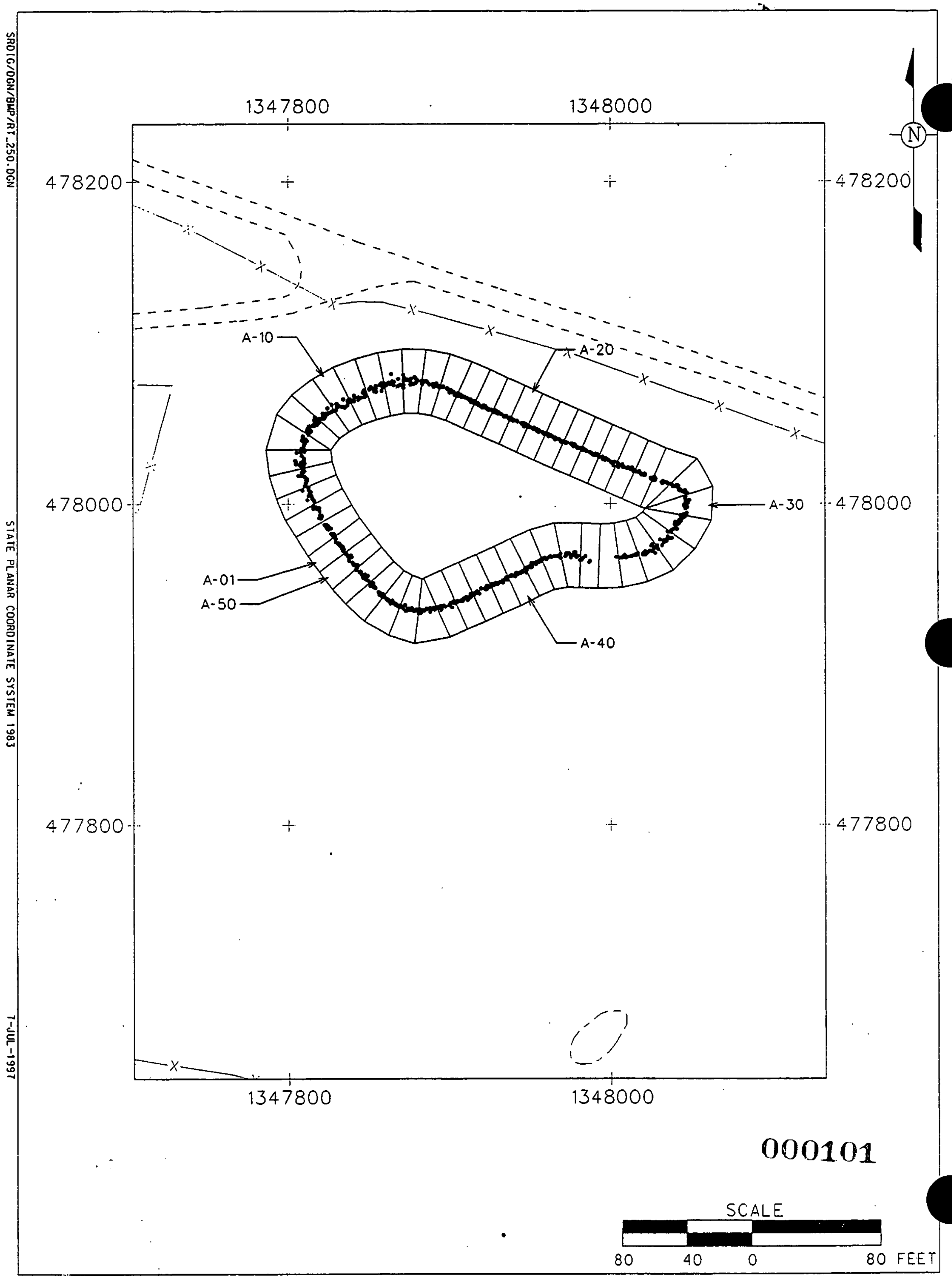

1347800
1348000
478200
478000
477800
N
A-10
A-20
A-30
A-01
A-50
A-40
SCALE
80
40
0
80 FEET

FIGURE 4-2A. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR SOUTH FIELD AREA - 2 M.P.H./ 2 SEC. ACQUISITION

1430



SRDIG/DGN/BMP/RT_250.DGN
STATE PLANAR COORDINATE SYSTEM 1983
7-JUL-1997
1347800
1348000
478200
478000
477800
N
A-10
A-20
A-30
A-40
A-01
A-50
SCALE
80
40
0
80 FEET

FIGURE 4-2B. CONFIGURATION AND MEASUREMENTS IN PROFILE SEGMENTS FOR SOUTH FIELD AREA - 1 M.P.H./ 4 SEC. ACQUISITION

5 1430

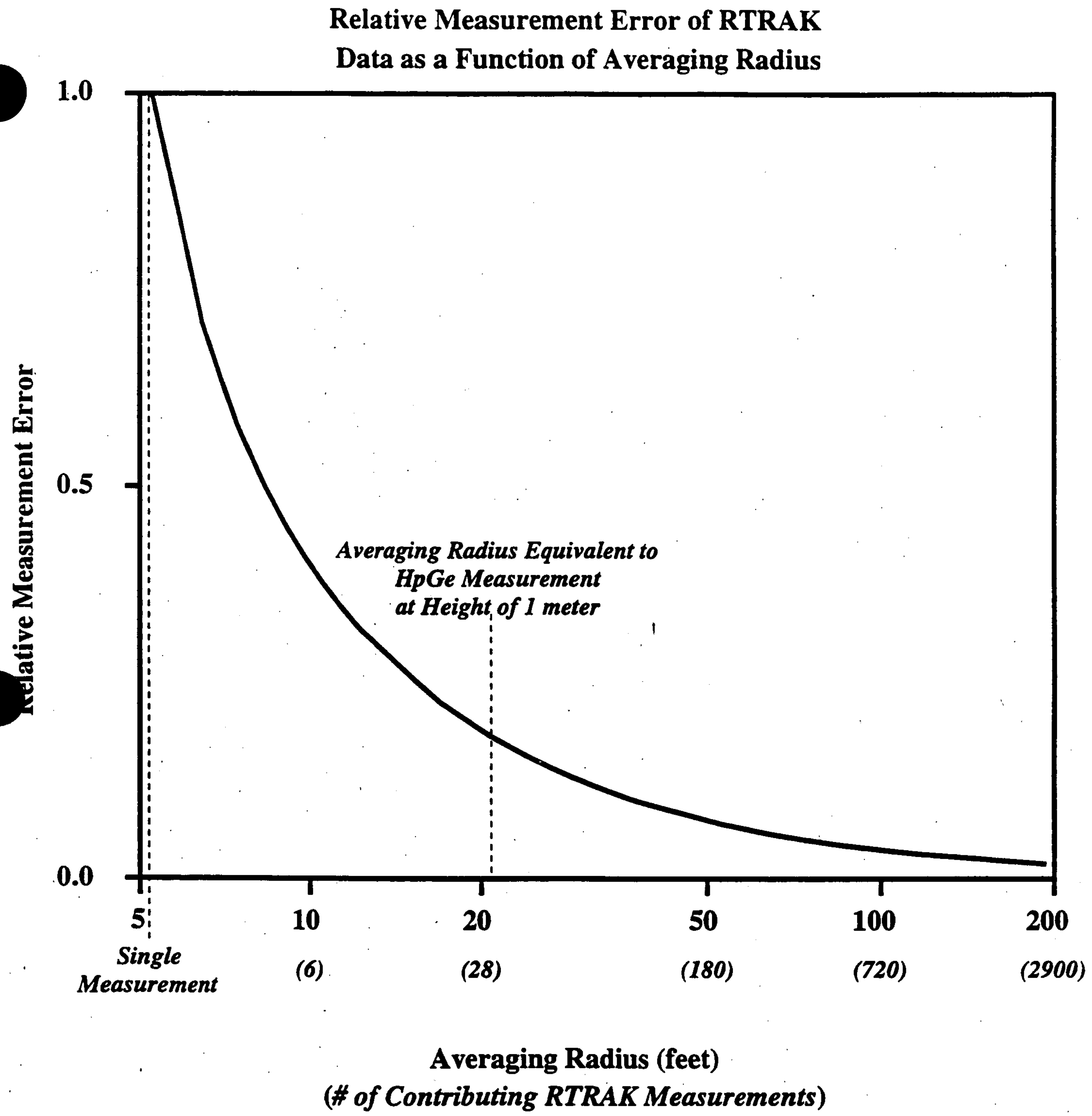


FIGURE 4-3
RELATIONSHIP BETWEEN MEASUREMENT ERROR AND AVERAGING RADIUS FOR RTRAK DATA

FIGURE 4-4
TOTAL URANIUM VARIABILITY AS A FUNCTION OF AVERAGING RADIUS

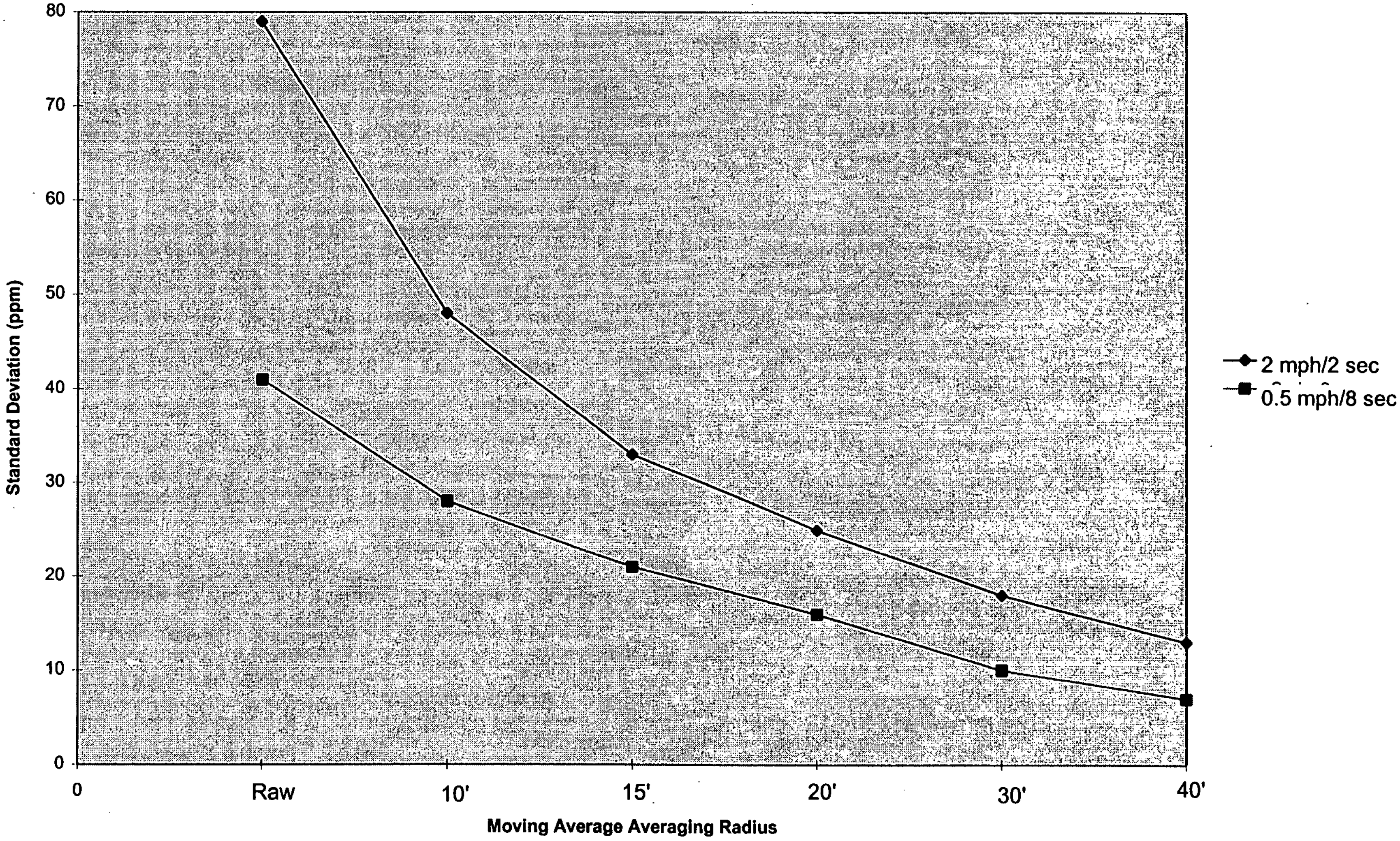


FIGURE 4-5
THORIUM-232 VARIABILITY AS A FUNCTION OF AVERAGING RADIUS

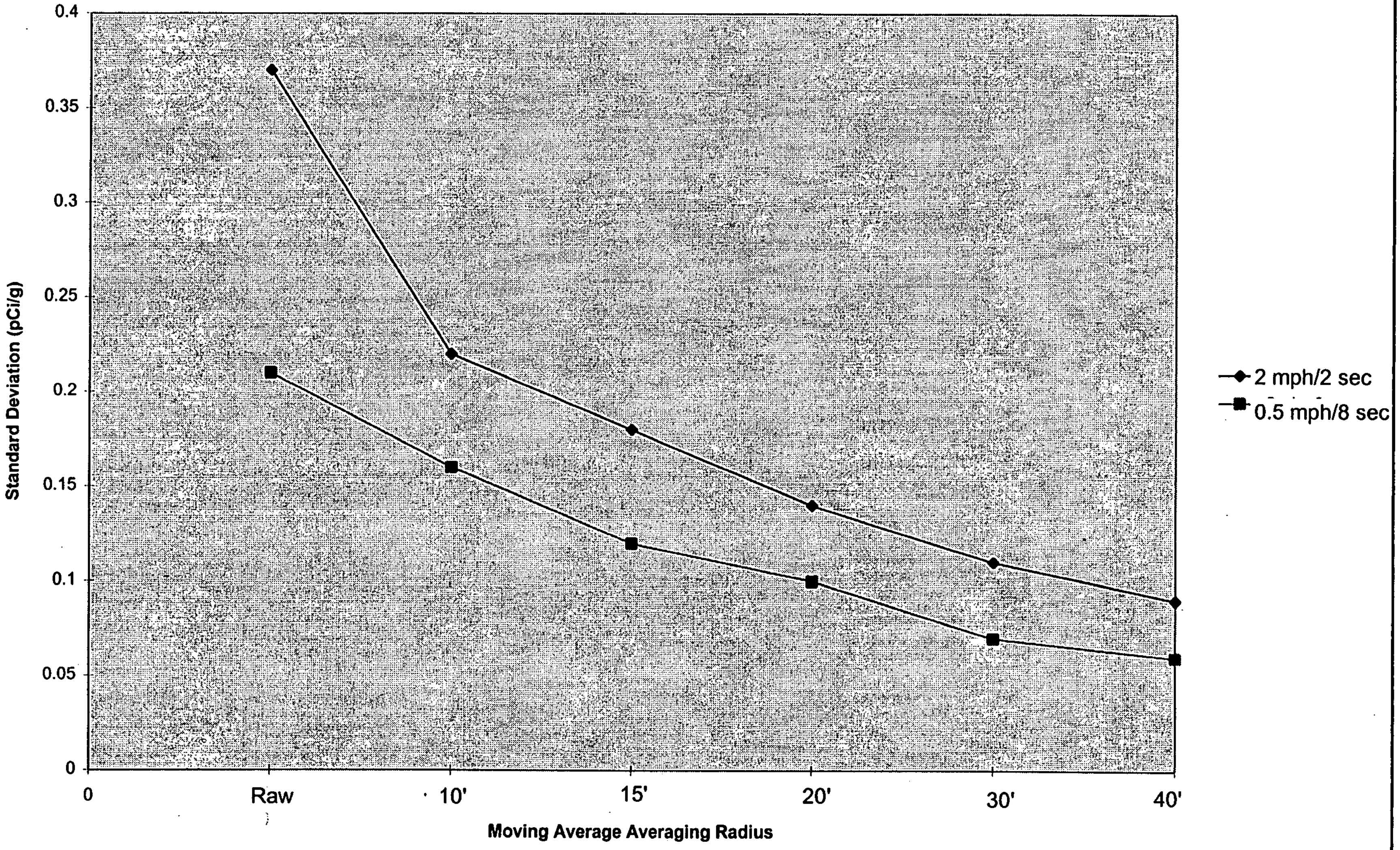
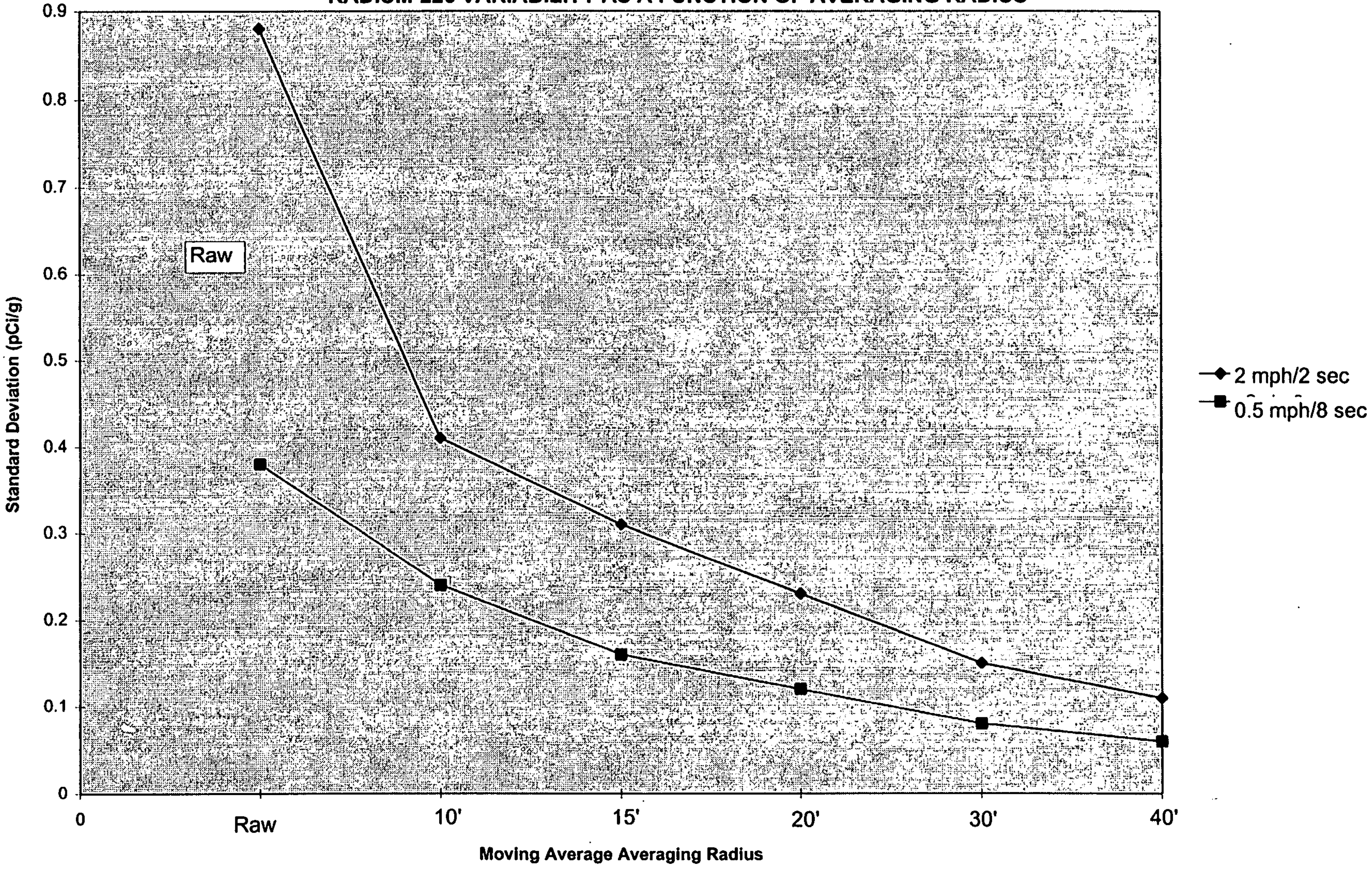


FIGURE 4-6
RADIUM-226 VARIABILITY AS A FUNCTION OF AVERAGING RADIUS



Section 5

SECTION 5.0
INTERFERENCES AND DATA REVIEW CRITERIA

5.1 SPECTRUM INTERFERENCES

The RTRAK system uses a NaI detector which has poor energy resolution in comparison to the germanium detectors typically used for gamma spectrometry. Consequently, it is not possible to readily separate peaks that are close to one another, and gamma photons with energies near those of analytes of interest can result in interferences that affect the validity of an RTRAK result. All three analytes of interest for RTRAK applications (uranium-238, thorium-232, and radium-226) can be affected by interfering gamma rays. The regions of interest for both the peaks and the backgrounds have been selected to minimize the interferences, and the calibration methodology attempts to take the interferences into account by utilizing multiple linear regression equations. However, when the activity of one or more of these analytes is significantly higher than the others, the interferences can be such that the results for the others will be inaccurate, irrespective of the compensating factors embodied in the calibration equations. The nature of gamma photon interferences are described below for thorium-232, radium-226, and uranium-238, and are summarized in Table 5-1.

5.1.1 Thorium-232

The gamma peak used for quantifying thorium-232 (from Tl-208) occurs at an energy of 2614 keV. There are no radionuclides present at the FEMP that will emit significant numbers of gamma rays at higher energies than either the peak or high-energy-background regions of interest for thorium-232. Consequently, the Compton continuum will contribute few counts in these regions and there are no interfering gammas at the high energy side of the peak or for the high-energy background. The low energy side of the peak and the low-energy background regions can experience interferences by gammas from the radium-226 decay chain. Bismuth-214, a radium decay product, has small abundance gamma rays at 2204, 2293, and 2448 keV. The 2448 keV peak falls within the Tl-208 peak region of interest, as will a portion of the 2293 keV peak. Some portion of all three bismuth-214 peaks will fall within the low-energy background region. Because these gamma rays have low abundances, they do hot have an appreciable impact on the thorium-232 result when the radium-226 concentration is comparable to or lower than the thorium concentration. But when the radium-226 concentrations are much higher than thorium-232 concentrations, the interferences could become significant and would probably lead to the thorium-232 data being biased low.

There are insufficient data available to accurately quantify the impact of these interferences or to accurately determine the radium concentration at which they become significant. Spectra from static RTRAK measurements were visually examined for apparent interferences. On the basis of these examinations, it appears that interferences may become significant when the radium-226 net counts per second exceed the thorium-232 net counts per second by more than 50 percent. However, the available data do not allow the magnitude of the interference to be estimated at this time.

5.1.2 Radium-226

The radium-226 is quantified by the 1764 keV gamma photon emitted by its decay product bismuth-214. A member of the thorium-232 decay chain, actinium-228, emits several gamma photons between 1588 and 1666 keV; the low energy background window for the bismuth peak is 1644.2 - 1693.4. One of the actinium-228 gamma photons falls within the background region, and the others can contribute to the total number of counts within the region. These gamma photons are low abundance, so they do not have a large affect when radium-226 and thorium-232 are present at comparable concentrations. However, in cases where the thorium-232 concentration is significantly higher than the radium-226 activity concentration, the interfering gamma rays significantly elevate the apparent background for the 1764 keV peak, resulting in an erroneously low value for the radium net counts per second.

There are insufficient data available to quantify the impact of these interferences or accurately determine the thorium concentration at which they become significant. Spectra from static RTRAK measurements were visually examined for apparent interferences. On the basis of these examinations, it appears that interferences may become significant when the thorium-232 net counts per second at 2614 keV exceeds 500; this is equivalent to approximately 30 pCi/g of thorium-232. The thorium-232 concentration at which the interferences become significant will depend upon the radium concentration; the higher the radium concentration, the higher the thorium concentration can be before the interferences become significant. Another indication of thorium decay chain interference are large negative radium-226 net counts per second. "Large" cannot be accurately quantified, but a rule of thumb of 20 negative net counts per second has been tentatively defined as the interference threshold. There are insufficient data at this time to either better define the interference level or to estimate the magnitude of the interference.

5.1.3 Uranium-238

The uranium-238 is quantified by the 1001 keV gamma peak form its decay product protactinium-234m. This peak is subject to interferences from the decay chains of both thorium-232 and radium-226. The peak region of interest as well as both the high and low energy background regions have interfering gamma photons. Interfering gamma photons from thorium decay products, thallium-208 and actinium-228 occur within all three regions. Gamma photons from radium-226 decay product, bismuth-214 occur within the peak region and the high energy background region; gamma photons from lead-214 are present within the low-energy background region. The 969 keV gamma photon from actinium-228 has an abundance of approximately 16 percent and so it presents interference problems regardless of the thorium concentration. However, it appears that this interference can be adequately accommodated by the calibration equations. The other gamma photons have low abundances, but at high thorium or radium concentrations, they become significant interferences, primarily by increasing the number of counts in the background regions. A clear indication of interference is a large negative values for the net counts per seconds for uranium-238. "Large" cannot be accurately quantified at this time, but a rule of thumb of more than 50 negative counts per second has been tentatively established. Thorium-232 activity in excess of 500 net counts per second is an indication of interference of thorium with the uranium peak. There are insufficient data to determine the radium threshold concentration for uranium interferences.

5.1.4 System Counting Rate Effects

When the RTRAK electronics are processing a signal from a gamma photon that has been detected, the system is insensitive or "dead" to additional signals. When counting rates are low, this does not cause any problems because, in most cases, the processing is finished before another gamma photon is detected. However, as the counting rate increases, the number of counts that can be lost will increase as well. The system analyzer monitors the time that signals are being processed and computes a "live time", when the system can receive incoming counts, and a "dead time" when the system cannot receive incoming counts. The dead time is often stated as a percentage of clock time or "real time". For the RTRAK system, the nominal acquisition time (e.g., 4 sec) is equivalent to the real time, and the RTRAK software outputs a value called the accumulation time which is equivalent to the live time. The percent dead time is then given by the relationship:

$$\%\text{Dead Time} = (T_R - T_L)\text{x}100/T_L$$

where:

T_R = real time or nominal acquisition time
T_L = live time or accumulation time as reported by the RTRAK software

The electronics in the RTRAK system provide corrections to the counting rates that are adequate for the intended uses of the RTRAK data. However, high dead times are an indicator of other potential problems, particularly what is known as pulse pile-up. Pulse pile-up occurs when signals from the detector enter the amplifier so rapidly that they cannot be completely separated and portions of one signal may be added to the previous one; that is, the signals may "pile up" on one another. Pulse pile up can lead to degraded spectrum resolution, spectrum shifts, and in extreme cases, a complete absence of peaks in the spectrum. Any of these can lead to incorrect analyte concentrations. The dead time can be used as an indicator of the potential for pulse pile up. A threshold of acceptability of 20 percent dead time has been established on the basis of visual examinations of RTRAK spectra. At dead times in excess of 20 percent, the RTRAK results are considered questionable because of pulse pile up.

High dead time does not mean that measurement data do not provide useful information. In fact it is an indication that there is a source of high activity nearby. That source could be "shine" from a large quantity of radioactive material near the measurement location, or it could be a result of high concentrations of one or more of the analytes within the measurement location. When high dead times are observed, the locations should be flagged as potentially high activity areas that must be investigated by other techniques for verification or quantification.

5.2 DATA EVALUATION

5.2.1 Raw Isotopic Data

The interferences discussed above must be considered when determining whether RTRAK data can be used directly or whether they should be considered questionable. A number of criteria have been developed that can be used to identify data requiring further investigation. These are addressed in Section 5.1 and are summarized in Table 5-2. The table identifies the source of each interference, the criterion for flagging the result, and the analytes affected. Exceeding one of the criteria does not indicate that the data should be rejected as having no useful information. In general exceeding one of the criteria is an indication of a source of high activity within or near the measurement location. Such locations should be further investigated using the in-situ HPGe or discrete sampling.

5.2.2 Total Activity Data

The total activity data are obtained from the sum of all counts observed in the RTRAK spectrum divided by the data acquisition time. The total activity per second results have a high degree of precision and may be effective in defining general patterns of contamination, but they do not provide radionuclide-specific information. A high gross counts measurement may be a consequence of high activity concentrations of any of the analytes of interest, or some unknown radio nuclide. Table 5-2 demonstrates the relationship between the total activity and the general levels of contamination. Elevated concentrations of uranium, thorium, and radium reflect an increase in the number of gross counts per second.

Because both thorium-232 and radium-226 have relatively high gamma ray intensities, the total activity is affected more by their presence at elevated levels in the soil as compared to comparable levels of uranium which has gamma intensities. A doubling of the thorium-232 or radium-226 above background will have a marked effect on the total activity whereas doubling background uranium would produce no measurable effect. Only with changes in the total uranium concentrations in the range of hundreds of ppm will the change be reflected in the total activity.

The data in Table 5-2 illustrate one risk inherent in the interpretation of the total activity data. The total activity in the South Field is about 17% higher than that in the USID area. However, the uranium-238 concentration in the South Field is approximately half the concentration in the USID area. Conversely, the radium-226 concentration in the South Field is approximately 1.75 times higher than in the USID area and the thorium-232 concentration is about 11% higher in the South Field. Thus although the total activity is approximately 400 cps greater for the South Field than for the USID area, the concentrations of the individual radionuclides in both areas are low and isotopic concentration differences doe not readily correlate with the difference in total activity.

Additional perspective in interpreting total activity data can be garnered by examination of Figure 5-1. Based upon RTRAK data collected in the Drum Bailing area (where total uranium concentrations cover a wide range), Figure 5-1 displays a general trend of increasing RTRAK total activity with increasing RTRAK total uranium concentrations. By bounding the data by upper and lower 95% confidence intervals from a regression analysis, a level of 18,000 cps can be assigned as an indication of potential WAC exceedances.

The following general guidance has been developed for the interpretation of total activity data:

1. Total activity below 3000 cps likely that total uranium, thorium-232, and radium-226 do not exceed the FRL. This applies for a total uranium FRL of 82 ppm, but does not hold for uranium FRLs of 10 or 20 ppm.

2. Total activity between 5000 and 15,000 cps likely indicates that one or more of the analytes - total uranium, thorium-232, or radium-226 - exceed the FRL or may indicat a hot spot exceedance. Total activity above 18,000 cps may indicate a WAC exceedance. Areas with total activity in excess of 18,000 cps should be confirmed by in-situ HPGe.

3. In a given area, a range of concentration differences of 50% (high total activity relative to low total activity) may indicate a significant increase in concentration of one or more analytes.

4. Total activity measurements are intended for field use provide guidance on the need for additional RTRAK or HPGe measurements. The analyte-sepcific results should be used for final interpretation of contamination patterns.

TABLE 5-1
SUMMARY OF GAMMA PHOTON INTERFERENCES

Radionuclide of Interest	Radionuclide of Emission	Energy of Gamma Photon Used for Quantification (keV)	Radionuclide Emitting Interfering Gamma Photon	Energy of Interfering Gamma Photon (keV)	Effect of Interference
Thorium-232	Thallium-208	2614	Bismuth-214 (from Ra-226 decay)	2204 2293 2448	Bias Th-232 low
Radium-226	Bismuth-214	1764	Actinium-228	1664-1666 (4 gammas) 1887	Bias Ra-226 low
Uranium-238	Protactinium-234m	1001	Thallium-208 (from Th-232 decay)	982	Bias U-238 high
				860 1093	Bias U-238 low
			Actinium-228 (from Th-232 decay)	969	Bias U-238 high
				944-1033 (7 gammas)	Bias U-238 high
				835 840 1065 1095	Bias U-238 low
			Bisumth-214 (from Ra-226 decay)	964	Bias U-238 high
				1069 1120	Bias U-238 low
			Lead-214 (from Ra-226 decay)	839	Bias U-238 low

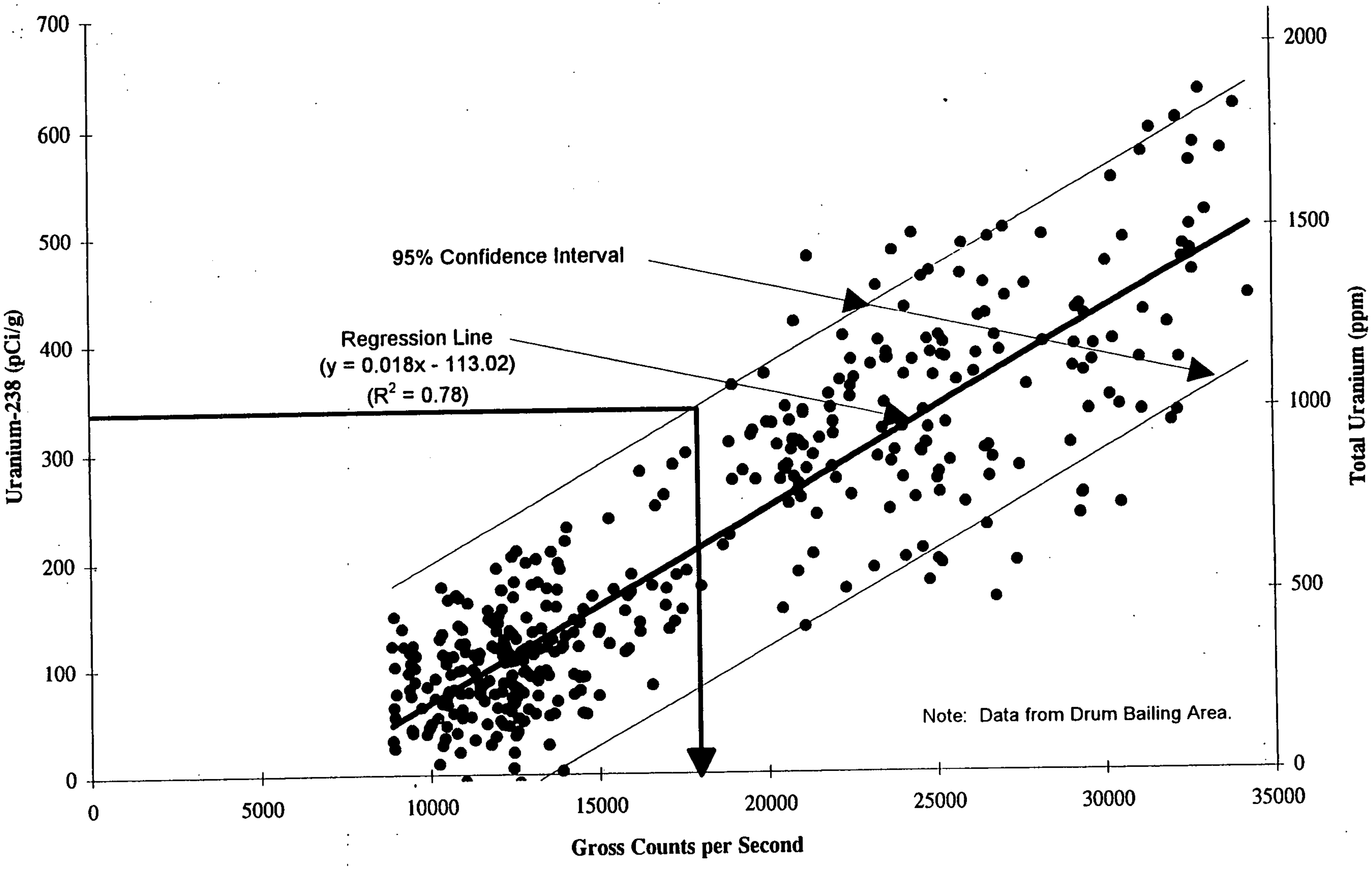
TABLE 5-2
INDICATORS OF POTENTIAL RTRAK INSTRUMENTAL PROBLEMS OR SPECTRAL INTERFERENCES DURING DATA ACQUISITION

Flagging Criterion	Interference Source	Analytes Affected	Comments
Dead Time > 20 %.	Counting Rate	Thorium Radium Uranium	May indicate high activity concentration of one or more analytes or nearby source of activity resulting in "shine"
More than 20 negative net thorium counts per second..	Spectrum shifts; Electronics failure	Thorium Radium Uranium	May indicate that spectrum shifts have caused peaks to fall outside of analyte regions of interest
Thorium net counts per second >500.	Thorium	Radium Uranium	May indicate that sources of high thorium activity are causing interferences.
More than 20 negative net radium counts per second.	Thorium	Radium Uranium	May indicate that sources of high thorium activity are causing interferences.
More than 50 negative net uranium counts per second.	Thorium Radium	Uranium	May indicate that sources of high thorium or radium activity are causing interferences.

TABLE 5-3
COMPARISON OF RTRAK GROSS ACTIVITY DATA TO RTRAK ISOTOPIC DATA AT 0.5 MPH WITH AN EIGHT SECOND DATA ACQUISITION TIME

Area	Uranium-238 (pCi/g)		Thorium-232 (pCi/g)		Radium-226 (pCi/g)		Gross Counts (cps)	
	Area Mean	Area Std. Dev.	Area Mean	Area Std. Dev.	Area Mean	Area Std. Dev.	Area Mean	Area Std. Dev.
USID	17.2	14.1	0.75	0.19	0.81	0.40	2456	176
South Field	9.71	14.3	0.83	0.22	1.38	0.47	2883	180
Drum Baling	209	69.8	3.83	0.78	8.46	2.44	15,703	2,298

FIGURE 5-1
URANIUM CONCENTRATIONS VS GROSS COUNTS



95% Confidence Interval

Regression Line
($y = 0.018x - 113.02$)
($R^2 = 0.78$)

Note: Data from Drum Bailing Area.

Section 6

E 1430

SECTION 6.0
SUMMARY AND CONCLUSIONS

RTRAK results were compared with HPGe and found to agree acceptably for both static and dynamic RTRAK measurements. For data from the USID area, the results of HPGe measurements were compared with the average results of RTRAK measurements that were within the HPGe field of view. These comparisons were performed for data from 8 sec/0.5 mph and 2 sec/2 mph runs. There is good agreement between the two systems for radium-226 and thorium-232 when their data are averaged over the whole area, with a slightly high bias present in the RTRAK. The agreement for uranium is not as good as for the 2 second/2 mph run, but becomes markedly better for the 8 second/0.5 mph run. This poorer agreement for uranium may be a reflection of the poorer precision seen for the 2 sec acquisition measurements. RTRAK measurements of radium-226, thorium-232, and total uranium are in good agreement with measurements of those radionuclides by HPGe in the Drum Baling Area, particularly given the heterogeneous nature of that area.

The results of the repeated profile measurements clearly show that counting uncertainties are major contributors to the overall standard deviations of the individual measurements, particularly at low concentrations. For uranium-238, thorium-232, and radium-226, the precision can be improved by increasing the acquisition time. The improvement is approximately proportional to the square root of the factor by which the acquisition time is increased. A similar effect is not observed for total activity results. This may be because the counting uncertainties are small for these measurements and other factors that are unrelated to acquisition time dominate the overall standard deviation.

Tables 4-10 a, b, and c summarize the contributions of various sources of uncertainty to the overall standard deviation of the measurements and provide an estimate of the total uncertainty at various concentrations. The concentrations include the FRLs, hot spot criteria, and the total uranium WAC. These estimates are based on the minimum expected standard deviations, counting uncertainties, and systematic uncertainties discussed in Section 4. Actual measurements are likely to have different total uncertainties primarily because of variations in the relative concentrations of the radionuclides.

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However, these estimates are adequate for planning purposes and have been incorporated in the calculation of trigger levels (Tables 4-15, 4-16, and 4-17).

The high standard deviations for the individual RTRAK measurements preclude their use at low uranium-238 and radium-226 concentrations and limits their use for thorium-232 at concentrations near background. However, at higher concentrations, the fractional standard deviation (standard deviation as a fraction of the concentration) becomes relatively small even for uranium. In addition, a number of measurements can be combined, or aggregated, to obtain a measurement with a lower standard deviation. The disadvantage to the use of aggregated measurements is that spatial resolution is lost. However, when the goal is to determine the concentration of an analyte averaged over a large area, the aggregation of a large number of measurements can provide data with a high degree of precision.

Total activity results have high precision for the individual measurements. This would allow these data to be used even at concentrations near background. Because these data provide no radionuclide-specific information, they are of only limited usefulness in cases where knowledge of concentrations of individual analytes is needed. However, general trends have been identified that allow the data to be of use in field evaluations of data. Evaluation criteria based on these trends are discussed in Section 5.2. In addition, because a single measurement covers an area of only 8.8 square meters, the total activity data can provide excellent spatial resolution when determining general patterns of contamination (total activity measurements do not have to be aggregated).

The MDCs for individual measurements exceed the FRLs for all three radionuclides of interest for 2 second acquisition-time measurements. For an acquisition time of 8 seconds, the uranium-238 individual measurement MDC still significantly exceeds the equivalent FRL of 27 pCi/g, while that of radium-226 is 93% of the FRL, and that of thorium-232 is 47% of the FRL. The effective MDCs can be reduced by using an aggregation of multiple measurements rather than relying on individual measurements. This is equivalent to averaging the data over a larger area than the RTRAK field of view. While this allows the applicability of the RTRAK to be extended to low concentrations, the spatial resolution is degraded.

The range of the RTRAK calibration has been extended to higher activity concentrations by performing measurements in the Drum Bailing Area. The calibration ranges now extend to the following maximum concentrations: 600 ppm for uranium-238; 5.8 pCi/g for thorium-232, and 20.5 pCi/g for radium-226. The extended range calibrations agree well with the original calibration equations for thorium-232 and radium-226. For concentrations of total uranium below 30 ppm, the new equations yield somewhat higher results than the original equations. At concentrations above approximately 60 ppm, the extended range calibration equations yield lower uranium-238 values than the original calibration. This occurs because the inclusion of higher concentration calibration data is better at compensating for high-concentration spectral interferences.

The relatively poor energy resolution of the detector in the RTRAK system results in a number of gamma photon interferences that must be considered in evaluating the data. Interferences are of particular concern in areas with high concentrations of thorium-232 or radium-226, which can lead to erroneous results. Effects and consequences of interferences and related phenomena are summarized in Tables 5-1 and 5-2.

The results and evaluations in this report lead to the following general conclusions:

1. **The preferred operating conditions are 4 second acquisition time with a travel speed of 1 mph.** The precision studies demonstrate that increasing the acquisition time improves the precision of the measurements. For the studies, the 8 second acquisition time provided the best precision. However, it is necessary to balance the precision against spatial resolution and logistical considerations. In order to maintain a constant field of view for the RTRAK in a dynamic mode, it is necessary to reduce the travel speed by a factor equivalent to any factor increase in the acquisition time. Experience in the field has shown that with the current engine speed and transmission of the it is difficult for the RTRAK operator to maintain a travel speed of below 1 mph while also adequately controlling the direction of travel. In addition, as the travel speed is reduced, the amount of time required to scan an area increases. If the required scanning time is too large, the utility of the RTRAK is reduced. The combination of 4 sec/1 mph was selected because it presented the best balance between precision and logistical consideration.

2. **The extended range calibration agrees well with the original calibration.** The agreement is good over the full range of concentrations evaluated for thorium-232 and

radium-226. For uranium-238, the new calibration yields high values at low concentrations (less than 30 ppm), apparently reflecting the low reliability of low-concentration measurements. At concentrations above 60 ppm, the extended range calibration yields lower values than the original calibration, reflecting the fact that the extended range calibration does a better job of accommodating and adjusting for interferences.

3. **Spectrum interferences increase as the concentrations of thorium-232 and radium-226 increase.** All three analytes of interest (uranium-238, thorium-232, and radium-226) are subject to interferences from one or more of the other analytes. Uranium-238 is the most severely affected. In areas where thorium-232 or radium-226 are of the order of tens of pCi/g the uranium-238 results are questionable, and spectra need to be carefully examined to determine whether the interferences preclude their use. Radium-226 results may also be affected when thorium-232 is in the range of 30 pCi/g or higher, and again, spectra must be examined to determine the impact of the interferences. At high radium-226 concentrations, thorium-232 may be biased low; data are not yet available to quantify the level at which the interferences become significant. Tables 5-1 and 5-2 summarize the interferences and criteria to be used to identify spectra requiring careful examination.

4. **High total uncertainties limit the usefulness of individual measurements at low concentrations.** For total uranium, the total uncertainty for a single measurement (4 sec/1 mph) at the FRL of 82 ppm is 64 ppm (78% of the FRL). At WAC levels, the total uncertainty for total uranium is 275 ppm, or 27% of the WAC. The percent uncertainties for thorium-232 and radium-226 are smaller than for uranium-238, but they are still significant for concentrations near the FRLs. At the FRL, the percent total uncertainty (at 4 sec/1 mph) is 25% for thorium-232 and 41% for radium-226. Total uncertainties are presented in Tables 4-10a, b, and c.

5. **Spatial averaging or aggregation of measurements can be used to improve precision, but at a loss of spatial resolution.** Individual measurements can be aggregated or spatially averaged to obtain a result with improved precision. When such averaging is performed, the appropriate precision parameter is the standard deviation of the mean which decreases with the square root of the number of measurements. However, aggregating measurements increases the size of the area for which the calculated value applies, thus degrading the spatial resolution. The effects of aggregating measurements is illustrated in Tables 4-11 and 4-12.

6. **Trigger levels can be used to facilitate the use of the RTRAK .** A trigger level is defined as a value, that if exceeded by a measurement, would require further action. The total uncertainties were used to calculate trigger levels that can be used during field activities. In order to achieve acceptable trigger levels, it is necessary, in most cases, to aggregate measurements. In general, aggregation of two consecutive measurements

is sufficient for WAC and hot spot determinations. Tables 4-15 through 4-19 provide trigger levels for various action levels such as FRLs and WAC.

7. **Total activity data (gross count rates) can be used for preliminary field screening and determining overall patterns of contamination.** Total activity data, or gross count rates, do not provide any information on specific radionuclide concentrations, and so are of limited value. However, these measurements exhibit high precision and provide excellent spatial resolution for determining overall patterns of contamination. An increase in gross counts means that one or more of the analytes of interest has increased in concentration, but it cannot be determined which analytes are responsible for the increase without further information. Despite that difficulty, an evaluation of the trends seen in the total activity has allowed the establishment of some general guidelines for its use in the filed. These guidelines are detailed in Section 5.2.2.

9. **The studies described in this report provide estimates of key quality parameters, uncertainty and minimum detectable concentration (MDC).** The repeated profile measurements provided the field measurement data to form the basis for calculating total uncertainties and analyte-specific MDCs. These are discussed in detail in Sections 4.3 and 4.5 respectively. Table 6-1 summarizes these parameters for the preferred set of operating conditions, 4 sec/1 mph.

TABLE 6-1
SUMMARY OF RTRAK QUALITY PARAMETERS

Quality Parameters 4 sec/1 mph	Uranium-238	Thorium-232	Radium-226	Gross Counts
Total Uncertainty (at the FRL[a])	64 pCi/g 192 ppm[b]	0.37 pCi/g	0.7 pCi/g	194 cps[c]
MDC[d]	57 pCi/g 216 ppm[b]	2.2 pCi/g	1.4 pCi/g	NA
Spectrum Interference	thorium radium	thorium	radium	NA

a For total uranium FRL of 82 ppm (equivalent to 27 pCi/g uranium-238)

b ppm refer to total uranium

c there is no applicable FRL for gross counts, this is the average standard deviation for South Field repeated profile measurements with an average mean of 2893 cps)

d MDC with a 4 second acquisition time is estimated from measurements with an 8 second acquisition time

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Appendix A

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APPENDIX A

THE RTRAK SYSTEM

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THE RTRAK SYSTEM

A.1 GENERAL DESCRIPTION

The RTRAK is a gamma-ray spectrometry system mounted on a four wheel drive John Deere tractor which serves as a mobile counting platform. This platform carries a low resolution 4 x 4 x 16 inch sodium iodide (NaI) detector connected to a high speed pulse height analysis (PHA) counting system. The counting system is mounted in and operated from the climate controlled tractor cab. The NaI detector with its associated photomultiplier tube (PMT) is insulated and mounted into a sealed 8 inch diameter PVC pipe to protect it from thermal and physical shock during field use. This pipe containing the NaI detector is suspended from the rear of the tractor and is at a height of 31 centimeters (1 foot) above ground level when in the measurement position.

A.2 SODIUM IODIDE DETECTOR

The gamma ray detector consists of a large single crystal of sodium iodide which is optically coupled to a photomultiplier tube (PMT). When radiation particles or rays strike the NaI crystal it emits light or scintillates. Detectors which work on this principle are referred to as scintillation detectors. It is crucial to the accuracy of devices which use this principle that the amount of light emitted when radiation strikes the detector be proportional to the energy absorbed by the crystal, which, in turn, is proportional to the energy of the radiation that caused the scintillation. The principle of scintillation is briefly discussed below.

When gamma rays emitted from radioactive nuclei strike the NaI detector, some or all of the energy of the gamma rays causes the atomic electrons to make transitions to higher energy states, thereby resulting in the absorption of the gamma rays. When these excited atoms return to their more stable ground state, the energy that was absorbed is re-emitted in the form of visible light. This process in which nuclear radiation impinging on a detector results in the production of light flashes or pulses is called "scintillation" and the detector is said to be a scintillation detector.

To be measured, the light emission must be converted to an electronic signal. This process occurs in the photomultiplier tube. Sodium iodide (NaI) detectors emit light that has too high a frequency to be seen in most PMTs. To shift the light frequency to a region visible by the PMT, an additive called an activator is added to the crystal. In NaI detectors the added activator is Thallium (Tl). When Tl is added to a NaI detector, it is more properly written as NaI(Tl).

When the PMT is optically coupled to the NaI(Tl) detector,. light photons emitted by the crystal strike a photosensitive surface in the PMT where the light energy causes one or more electrons to be ejected from the "photocathode." These liberated electrons strike electron multiplier plates inside the PMT called dynodes and the signal is amplified to a level that can be registered by readout circuitry such as a pulse height analysis system (PHA). The height of the resultant voltage pulse is proportional to the energy of the radiation that caused it.

In the NaI(Tl) detector the minimum energy required to record a radiation event is quite high compared to that required by a high purity germanium (HPGe) detector. In order for a signal to be generated, an electron in the crystal must be excited from the valence band to the conduction band. When the excited electron returns to a lower energy state, light photons are emitted. For NaI(Tl) crystals this process requires approximately 30 eV of energy. By comparison, the corresponding process in a HPGe detector requires only about 0.6 eV. Because the NaI(Tl) requires so much more energy to produce a detection signal, its energy resolution is much poorer than a HPGe detector. In practical terms, this means that the peaks in a NaI spectrum are much broader than those in a HPGe spectrum. If you used both detectors to look at a radioactive standard containing cesium-137 (Cs-137), the NaI detector would result in a peak full width at half the maximum peak height (FWHM) of about 55 Kev, whereas the HPGe peak width would be approximately 2 Kev. This means that two gamma rays which differ in energy by 30 to 40 Kev would appear as one broad peak in a sodium iodide spectrum, but they would appear as two well separated peaks in a HPGe spectrum. The lower resolution of sodium iodide detectors does present some limitations on their use, but these are not serious limitations in most situations encountered at the FEMP.

A.3 MULTI-CHANNEL PULSE HEIGHT ANALYSIS SYSTEM

The technique of gamma ray spectrometry makes use of the fact that the energy of many gamma photons are a unique characteristic of the particular isotope which emitted them. Much like a human fingerprint can be used to identify an individual, when gamma photons are detected they indicate the presence of specific isotopes. For example, all potassium-40 (K-40) nuclei emit photons with an energy of 1460.8 Kev, while Cs-137 nuclei emit gamma rays with an energy of 661.6 Kev. As stated above, the NaI detector is a useful tool for the measurement of gamma ray energies because the height of the output voltage pulse from the PMT is directly proportional to the energy of the photon which initiated it. Thus we can determine the number of gamma rays of a specific energy which are detected in a fixed period of time by counting the number of voltage pulses which are generated in the PMT with a certain height. This number is related to the amount of a specific radioactive isotope which is emitting the detected gamma rays.

The function of determining pulse heights and counting them is performed electronically by an instrument called a multichannel pulse height analyzer (MCA). This instrument measures the height of each voltage pulse coming from the photomultiplier tube and counts the number of pulses that occur in each one of a set of predefined voltage ranges. A separate count of the number of pulses that occurs in each range is performed simultaneously and stored in unique memory registers called channels, with one channel for each voltage. Since the pulse heights are proportional to the energies of the gamma rays that were responsible for the generation of the pulses, the MCA system allows the collection of a gamma ray energy spectrum, which can be analyzed to identify and quantify radioactive isotopes that are present within the detector's field of view. The MCA instrument permits the simultaneous identification of many nuclide decay energies during a single analysis. The RTRAK PHA counting system is coupled to a computer containing commercially available gamma spectral analysis software. Gamma peaks displayed in the spectrum are identified by comparing the peak energies to known characteristic isotopic photon decay energies contained in a "reference library." For gamma-emitting nuclides, the net peak area is divided by the counting time and multiplied by a conversion or counting efficiency factor to quantitatively determine the concentration of each identified nuclide. The RTRAK counting system may also be used as a gross survey instrument by summing the total counts in the spectrum. This feature is useful in discriminating between areas of high and low activity.

A.3.1 RTRAK Energy Calibration

Since the pulse height is proportional to the energy of the gamma ray that was responsible for the generation of the pulse, the MCA system allows the collection of a gamma ray energy spectrum. The output of the MCA is a gamma ray spectrum which consists of a count of the number of gamma photons detected as a function of the photon energy. Peaks in these spectra occur at energies which are characteristic of the radionuclides present in the soil and other surroundings. But, in order to make use of this information, the energy at which the spectral peaks occur must be identified. The process of

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energy calibration is accomplished by exposing the NaI detector to a radioactive source which contains radioisotopes of known identity. By knowing the energy of the photons emitted by the isotopes in the radioactive source and identifying from the accumulated spectrum the channel number where the maximum count in each peak occurs, one can develop an equation which describes the relationship between the channel number at which a spectral photopeak occurs and the energy of that photopeak.

This process is described in FEMP procedure EQT-30, "Operation of Radiation Tracking Vehicle Sodium Iodide Detection System." Lantern mantles containing radioactive thorium-232 (Th-232) and its decay progeny are used as an energy calibration source for the RTRAK. This is a particularly convenient source to use for calibration because it emits both low energy and high energy gamma rays which span the energy region of interest for the remediation projects at the FEMP. The RTRAK detector system is energy calibrated before each use by placing the thorium mantle in the center of the detector housing and acquiring a spectrum. If necessary, the pulse amplifier is adjusted so that the centroid of the photopeak at energy 238.6 Kev falls in MCA channel 40, while at the same time, the centroid of the photopeak at energy 2615 Kev falls in channel 447. Lead-212 (Pb-212) is the source of the 238.6 Kev gamma ray, while the 2615 Kev gamma ray originates from thallium-208 (Tl-208). Both of these isotopes are radioactive daughters of Th-232. When the system is adjusted as described above, the slope of the energy versus channel number graph is equal to 5.85 Kev per channel. Thus a peak which appeared in channel 171 would correspond to an energy of 1000 Kev (171 times 5.85). Peaks do appear in RTRAK spectra near this channel and they may be attributed to the 1001 Kev peak from Pa-234m, a radioactive daughter of U-238. The presence of a peak at this energy is used by the FEMP in-situ measurements staff to infer the presence of U-238 in the soil scanned by the RTRAK.

As noted earlier, sodium iodide is a low resolution detector which results in fairly broad peaks in the accumulated gamma spectra. Regions of interest (ROIs) which span the full width of each photopeak must be defined and the counts in all the MCA channels within the ROI must be summed to ensure counting all the events associated with a particular gamma emission. The regions of interest or energy windows for the primary radiological contaminants of concern at the FEMP are given in Table A-1. The boundaries of the windows are chosen so that they are wide enough to accept as many counts as possible from the nuclide of interest without allowing undue interference from other peaks in the spectrum. Also shown in Table A-1 are the windows used to subtract the background from the signal windows. These also represent a compromise between windows wide enough to accurately characterize the background near the peak of interest and windows narrow enough to exclude interferences from other photopeaks. As described elsewhere in this report, steps must be taken when developing the calibration equations to compensate for interferences in both the signal and background windows.

A.3.2 RTRAK Efficiency Calibration

After properly completing an energy calibration, the NaI detector can be used to determine the identity of the radioisotopes in the soil scanned by the RTRAK provided that the photon energies are at least 70 Kev apart. However, in order to use the RTRAK to also determine how much of each radionuclide is present, one must relate the number of gamma ray counts of a particular energy registered by the counter to the amount of the corresponding radionuclide present in the in the soil. In a laboratory setting, this would be accomplished by reproducibly positioning and counting a container filled with an accurately known quantity of a radioactive standard for a fixed period of time. Such radioactive standards may be purchased along with certificates documenting their activity from the National Institute of Standards and Technology (NIST) or other vendors who maintain measurements programs which are traceable to NIST. The detection efficiency would be computed simply as the ratio of the number of gamma photons of a specified energy detected in a fixed period of time divided by the number of photons of that energy emitted by the standard in the same time interval. Since some of the photons emitted from the standard don't travel toward the detector, while others travel through the detector material without interacting at all, the computed efficiency will be a number between zero and one. The efficiency will vary with photon energy. If all the measurement conditions that prevailed during efficiency calibration are the same when samples are counted (e.g., distribution of radionuclides in the material being counted, the size, shape and composition of the counting container, and the relative position of container and detector) the measurement process will be accurate.

Since the RTRAK was designed as an in-situ measurement system, it is not practical to purchase and use certified standard materials to reproduce the calibration process described above. However, if one has multiple field locations which have been accurately characterized, these may be used to experimentally determine the relationship between the concentration of a particular radionuclide in the soil and the count rate detected by RTRAK for that isotope. This process was described in the July, 1997 RTRAK Applicability Study. This study made use of a separate study conducted at the FEMP in which the comparability of laboratory analyses with in-situ gamma spectrometry measurements using hyper-pure germanium detectors (HPGe) was demonstrated. The present RTRAK study makes use of the same calibration technique, but the calibration range is extended to higher analyte concentrations.

As in the previous RTRAK report, the efficiency of the RTRAK detector was determined by comparing static RTRAK measurements to HPGe readings at the same locations. HPGe measurements taken with a detector height of 31 cm were used as the basis for "known" concentrations of U-238, Th-232, and Ra-226. This height was used because it gave the best match between the fields of view of the two detectors. Multiple linear regression analyses of the net RTRAK counts per second versus the soil radionuclide concentrations were performed to derive a calibration equation which can be used to compute isotopic concentrations in the soil from the net count rate from each isotope. When the calibration was extended to higher concentrations, interferences not evident in the earlier study became apparent, and it became necessary to use multiple linear regressions to derive the calibration equations.

The data which were used to develop RTRAK calibration equations are shown in Table A-2. It consists of data collected at the ten field locations used in the Part B Comparability Study plus an additional eight locations in the Drum Baling area, the USID area, and the South Field area of the FEMP. At each location, 31 cm HPGe measurements and 300 second static RTRAK measurements were performed. Multiple linear regression analyses were performed to determine the relationship between the net RTRAK count rates for each contaminant isotope and the HPGe measurements. The method for obtaining the net count rate for each peak of interest is discussed in section A.5.1 of this appendix. The regression analyses resulted in the following equations for quantifying RTRAK net count rates. In the equations below, the subscripted quantities are the Net Counts Per Second for the particular analyte.

Thorium-232 Calibration Equation

The thorium-232 calibration equation from the previous revision of this report (i.e., the old calibration equation) is shown below:

$$\text{RTRAK Th-232 pCi/g} = 0.06817 * \text{Th}_{\text{NCPS}} - 0.041$$

The extended range calibration equation for Th-232 (i.e., the new calibration equation) now becomes:

$$\text{RTRAK Th-232 pCi/g} = 0.05725481 * \text{Th}_{\text{NCPS}} - 0.0044179 * \text{Ra}_{\text{NCPS}} + 0.09624421$$

Note: The Ra-226 count rate effects the RTRAK thorium result because of contributions to the thorium signal window which arise from low abundance radium daughters. This interference becomes important at higher radium concentrations.

Radium-226 Calibration Equation

The old radium-226 calibration equation was:

$$\text{RTRAK Ra-226 pCi/g} = 0.19243 * \text{Ra}_{\text{NCPS}} + 0.08805$$

Thew new Ra-226 calibration equation now becomes:

$$\text{RTRAK Ra-226 pCi/g} = 0.12145634 * \text{Ra}_{\text{NCPS}} + 0.01735413 * \text{Th}_{\text{NCPS}} + 0.13277316$$

Note: Low abundance gamma rays from Th-232 daughters contribute counts to the background windows for Ra-226. If this interference was not considered, the normal mode of background correction would overcompensate, thus yielding Ra-226 results with a low bias. The thorium term in the Ra-226 equation above compensates for this overcorrection.

Uranium Calibration Equation

As it appeared in the July 1997 RTRAK report, the uranium-238 calibration equation was originally written in terms of the uranium-238 net counts per second and the radium-226 and thorium-232 activity concentrations as follows:

$$RTRAK\,U\text{-}238\,pCi/g = 2.994[U_{NCPS} - [\frac{Th\text{-}232\,pCi/g}{0.135} + \frac{Ra\text{-}226\,pCi/g}{0.271}]] + 0.481$$

This may be rewritten in terms of the net counts per second for all three isotopes by substituting the old radium and thorium equations into the uranium-238 equation and rearranging the resulting terms. The recast form of the old uranium-238 calibration then becomes:

$$\text{RTRAK U-238 pCi/g} = 2.994\ \text{U}_{\text{NCPS}} - 1.5118591\ \text{Th}_{\text{NCPS}} + 2.1259610\ \text{Ra}_{\text{NCPS}} + 1.904$$

The new U-238 calibration equations are shown below in units of U-238 pCi/g and total uranium ppm.

$$\text{RTRAK U-238 pCi/g} = 0.95562898 * \text{U}_{\text{NCPS}} - 0.4031465 * \text{Th}_{\text{NCPS}} + 1.01951125 * \text{Ra}_{\text{NCPS}} + 9.408$$

$$\text{RTRAK Total U ppm} = 2.86307076 * \text{U}_{\text{NCPS}} - 1.20782959 * \text{Th}_{\text{NCPS}} + 3.05446247 * \text{Ra}_{\text{NCPS}} + 28.186$$

Note: Two equations are provided for uranium so that either set of units will be readily available to a user. The second equation is derived from the first by making use of known constants and weight to activity conversion factors, and further assuming that the uranium encountered in the soil will be of normal enrichment. Uranium experiences interferences in both the signal window and the background windows. Th-232 daughter gamma rays at 969 Kev contribute to the signal window, while Ra-226 daughter gamma rays at 1120 Kev contribute to the background window. Thus a term proportional to the Th-232 activity must be subtracted from the counts in the signal window, while a term proportional to the Ra-226 activity must be added back in to compensate for the overcorrection due to the elevated background counts.

A.4 GLOBAL POSITIONING SYSTEM

The physical location at which each spectrum was acquired is determined using a global positioning system (GPS). The GPS system used at the FEMP utilizes two receivers, a Pathfinder ProXL system and an Omnistar 6300A. These receivers are mounted in the climate controlled tractor cab and antennae for the systems are mounted on the cab roof. The Omnistar receiver is used to provide real-time differential correction to the Pathfinder receiver, increasing position accuracy. In essence, the Omnistar receiver acts as a "virtual base station". Operating in the differential mode allows sub-meter position accuracy. (Note: Without the differential processing capability, position errors up to approximately 100 meters can exist). When counting is performed using the RTRAK system, special software developed for RTRAK called MULTIACQ tags the spectrum with location coordinates provided by the GPS system.

A.4.1 Operation of the GPS

The GPS is started and checked before the RTRAK unit proceeds to the field for measurements. The technique for start-up and checking is as follows:

- Turn on the GPS and differential GPS (DGPS) receivers.
- Allow five minutes for the receivers to warm up.
- Ensure that the GPS and DGPS antennae mounted on the tractor cab are intact and undamaged.

After startup, the GPS will automatically lock onto satellites during the warm-up. The unit is designed to lock onto US Defense Department satellites named "NAVSTAR." There are 24 NAVSTAR satellites in polar orbit that make up the GPS constellation. Twenty-one of these are in operation at all times and three are spares. The GPS information is read out to a Magellan NAV 5000 Receiver. This receiver displays location information and, if the station is moving, also displays the rate of speed. The GPS rate of speed in miles per hour is used by the RTRAK driver to control the survey speed.

An investigation has revealed that when the GPS system does not receive "clean" satellite signals, erroneous location coordinates or other erroneous file parameters are associated with the measurement. Because the actual location of these measurements cannot be determined, the data must be discarded. The problem arises when measurements are being made in locations having obstructions that may interfere with the receipt of the satellite transmission, such as trees or buildings. Such obstructions are, in part, a consequence of the position of the satellite at the time the measurement is made. In locations where obstructions are not severe, clear signals can be received during certain periods of the day. Measurements with GPS problems can be identified by an examination of the RTRAK data files. This examination has been included as one of the routine data quality checks for the RTRAK measurements.

A.5 RTRAK OPERATION

The RTRAK may be operated in the static mode or the mobile mode. In the static mode, i.e. the RTRAK vehicle remaining stationary, the operator initiates a count for a specified amount of time. At the end of the counting period, the collected spectrum is saved to electronic media for later data reduction.

In the mobile mode, a special computer program called MULTIACQ is used to provide a continuous collection of spectra once the counting time is set and the GPS coordinate data are incorporated. When this program is initiated, spectra will continue to be consecutively collected at the specified counting time until the operator stops the counting process. The counting times presently used for RTRAK spectrum collection range from two to eight seconds.

Standard mobile operation of the RTRAK consists of driving the tractor at approximately two miles per hour (~ 3 ft/s) over an area to be measured and collecting, GPS tagging and storing a spectrum every two seconds. Each two second measurement integrates the concentration over approximately 10 square meters. Alternatively, the tractor may be operated at a speed of one half mile per/hr (~ 0.75 ft/s) while collecting data every two seconds or every eight seconds. Slowing the RTRAK down, counting longer, adding detectors or averaging over a larger area reduces the relative error of the data collected by roughly the square root of the change in counting time.

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Windows or regions of interest for those nuclides of interest are noted in the RTRAK spectra, and then the net counting data determined from these windows are quantified. The windows used for RTRAK spectra are given in Table A-1.

A.5.1 Quantification of Nuclide Data

To obtain net counts for each of the measured nuclide signal windows, the integrated counts of the two background windows are summed and then normalized to the width of the signal window. The normalized value is subtracted from the integrated signal window counts. This technique is illustrated in Figure A-1. The normalized "counting backgrounds" for each signal window are shown as cross hatching under each of the peak (signal window) areas. The upper black area of the peak is the resultant net counts for each peak. Figure A-1 also illustrates why the uncertainty in RTRAK measurements tends to be large. The "counting background" is substantially larger than the measured net peak counts; but both background and net counts contribute to the uncertainty. These large uncertainties occur as a result of short spectrum count times (2 or 8 seconds) and because we are often measuring activity that is at or just above background concentrations.

The resulting net counts are divided by the count time (4 seconds) to compute a net count rate for the signal window with units of counts per second (cps or ncps). The signal net counts per second are then inserted into appropriate "calibration equation" to yield a quantified activity concentration in pCi/g. These data are also saved to electronic media for later data reduction and contour mapping.

A.6 PLANNED RTRAK SYSTEM UPGRADES

In December 1997, DOE was awarded funding for a proposal to deploy an integrated suite of technologies to be used in delineating contamination in soils in support of soil remedial actions at the FEMP. Fluor Daniel Fernald, the Environmental Assessment Division of Argonne National Laboratory, the DOE Environmental Measurements Laboratory, and the Idaho Environmental and Engineering Laboratory were partners in the proposal with DOE. The technologies to be deployed were the RTRAK mobile NaI detection system, which is the subject of this report, and multiple HPGe gamma spectrometry systems along with technologies to make the processes of data acquisition and resuction, data transfer and storage, and mapping of results more reliable and more automated. Important objectives of this Accelerated Site Technology Deployment (ASTD) project are:

1. To automate the process by which data are transferred from the field to the Sitewide Environmental Database (SED),

2. To expedite the uploading of in-situ soil remediation measurements to make them available on the world wide web to regulators and other interested stakeholders within 24 hours of data acquisition,

3. To facilitate production of maps in real time as an aid to the remediation decision making process during excavation work,

4. To provide RTRAK operators in the field with a reliable means of determining areas that have been scanned, and

5. To provide RTRAK operators real time readouts of the results of their measurements and of equipment status.

With the funding provided by DOE over the next three years, improvements will be made to the RTRAK funding system hardware and software. New gamma spectrometry software will be purchased. New GPS hardware will be purchased to make GPS positional data acquisition more reliable and to facilitate the production of maps which display radionuclide contamination levels. Wireless data transmission equipment will be purchased to permit automated downloads of field data from the RTRAK and multiple HPGe detectors. Mapping software will be purchased. A smaller version of the RTRAK will be developed for use in wooded areas or trenches that are inaccessible to the RTRAK. Obviously, some of the manufacturers' names and model numbers and some of the software packages mentioned in the ASTD will change. Despite the numerous changes that are being planned, all the important capabilities of the current RTRAK system will be maintained or improved.

TABLE A-1

ENERGY WINDOWS USED FOR RTRAK SPECTRA

Measured Nuclide	Measured Nuclide Energy, keV	Gamma Photon Abundance (%)	Nuclide of Interest	Low Background Window keV	Signal Window keV	High Background Window keV
Pa-234m	1001.0	0.00845	U-238	836.6-865.8	943.1-1058.9	1064.7-1093.8
Tl-208	2614.44	0.3586*	Th-232	2370.3-2399.5	2405.4-2823.8	2829.6-2858.9
Bi-214	1764.49	0.158	Ra-226	1644.2-1693.4	1699.3-1850.9	1856.7-1886.0
K-40	1460.81	0.1067	K-40	1308.8-1338.0	1343.9-1577.7	1583.5-1612.8

*Includes a 0.359 branching ratio of decay of Bismuth-212.

TABLE A-2

RTRAK CALIBRATION DATA USED TO PERFORM MULTIPLE LINEAR REGRESSIONS TO OBTAIN CALIBRATION EQUATIONS

MEASUREMENT LOCATION	RTRAK NET CPS			0.31 m. HPGe pCi/g		
	U-238	Th-232	Ra-226	U-238	Th-232	Ra-226
A3-11	68.7	67.7	137.1	200.0	3.49	20.5
A11-3	12.6	13.6	4.3	25.2	0.93	0.887
A13-3	43.6	79.1	1.3	9.5	4.14	1.15
A15-2	7.8	13.4	5.3	5.2	0.82	1.21
A9-1	2.9	10.8	4.7	2.9	0.67	0.744
A11-4-1	9.1	13.5	4.9	15.35	0.90	0.871
A11-5-2	8.8	13.8	4.3	21.1	0.91	0.93
A3-12-4	69.5	43.4	137.6	180	1.76	14.7
PBC-01	3.3	8.4	3	3	0.52	0.64
PBC-02	4.1	14.8	2.9	10.4	0.64	0.665
PBC-03	16.6	24.9	28.6	75.8	1.80	6.0
PBC-04	8.7	12.3	4.1	18.9	0.80	0.825
PBC-05	5.8	12.2	3.6	14.1	0.80	0.715
PBC-06	11.7	12.4	4.4	25.6	0.81	0.802
PBC-07	19.5	14.8	5.4	47.1	0.99	0.8
PBC-08	2.2	9.3	3.6	2	0.56	0.65
PBC-09	3	10.1	3.6	2.2	0.63	0.73
PBC-10	52.1	94.7	4.9	27	5.82	1.875

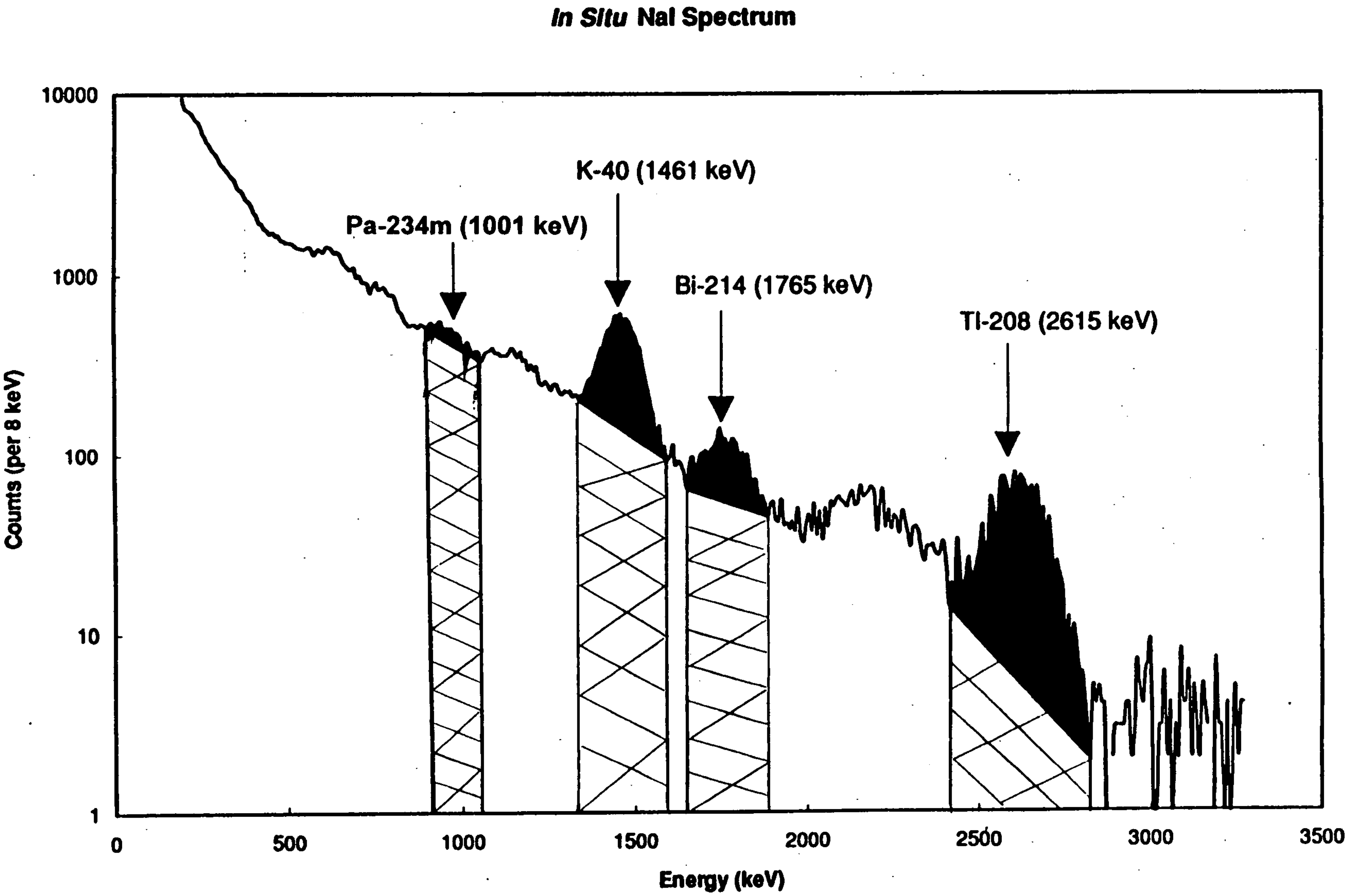
In Situ NaI Spectrum
10000
1000
100
10
1
Counts (per 8 keV)
0
500
1000
1500
2000
2500
3000
3500
Energy (keV)
Pa-234m (1001 keV)
K-40 (1461 keV)
Bi-214 (1765 keV)
Tl-208 (2615 keV)

Figure A-1

Appendix B

APPENDIX B

PROFILE RUNS FOR USID, SOUTH FIELD, AND DRUM BALING AREAS

APPENDIX B
PROFILE RUNS FOR USID, SOUTH FIELD, AND DRUM BALING AREAS

Appendix B contains tables and figures presenting data obtained from repeated measurements along pathways in the USID, South Field, and Drum Baling areas. Tables B-1, B-4, B-7, and B-10 present data for the USID area, while Tables B-2, B-5, B-8, and B-11 present data for the South Field, and Tables B-3, B-6, B-9, and B-12 present data for the Drum Baling area. Each table shows the number of segments into which the pathway is subdivided, as well as the number of measurements for each segment. The mean, standard deviation, and percent standard deviation (relative to the mean) of the measurements in each segment are also shown. Grand averages of the mean, standard deviation, and percent standard deviation are also calculated for each pathway.

Figures B-1 through B-33 are graphical presentations of the means, standard deviations, and standard deviations as a percentage of the means contained in Tables B-1 through B-12.

TABLE B-1

URANIUM-238 (pCi/g) - REPEATED PROFILE RUNS IN USID AREA

		2 sec - 2 mph				2 sec - 0.5 mph				8 sec - 0.5 mph		
AREA	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV
A-01	41	11.50	25.36	220.52	129	5.61	27.76	494.83	27	16.33	12.80	78.38
A-02	71	8.57	25.76	300.58	217	9.97	27.11	271.92	52	11.92	12.53	105.12
A-03	73	14.58	26.20	179.70	206	14.43	26.73	185.24	44	16.80	12.77	76.01
A-04	72	16.41	25.76	156.98	205	13.73	24.58	179.02	50	20.09	14.84	73.87
A-05	76	15.51	25.59	164.99	216	18.37	25.98	141.43	47	16.97	14.53	85.62
A-06	73	17.04	26.18	153.64	225	11.54	27.71	240.12	43	17.01	15.07	88.59
A-07	69	13.91	23.27	167.29	200	17.65	28.69	162.55	46	19.78	13.31	67.29
A-ROAD	52	13.21	21.82	165.18	120	6.46	21.34	330.34	28	8.49	14.21	167.37
A-08	75	24.47	28.02	114.51	231	19.01	26.45	139.14	49	20.47	16.01	78.21
A-09	84	29.00	28.34	97.72	232	21.78	28.04	128.74	53	22.01	15.02	68.24
A-10	80	23.83	24.08	101.05	240	20.03	29.53	147.43	55	21.33	13.27	62.21
A-11	73	12.76	29.5	231.19	193	13.96	25.95	185.89	44	14.70	14.82	100.82
Averages		16.73	25.82	171.11		14.38	26.66	217.22		17.16	14.10	87.65

TABLE B

URANIUM-238 (pCI/g) - REPEATED PROFILE RUNS - SOUTH FIELD

	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
AREA	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV
A-01	42	1.13	25.07	2218.58	15	17.41	18.36	105.46	16	-5.55	15.31	275.86
A-02	38	11.82	29.77	251.86	15	11.53	18.57	161.06	14	8.70	12.07	138.74
A-03	43	22.26	26.38	118.51	16	9.84	19.20	195.12	17	9.83	14.27	145.17
A-04	44	4.62	31.36	678.79	17	16.09	25.47	158.30	15	16.73	17.51	104.66
A-05	42	17.11	38.03	222.27	17	13.59	19.69	144.89	16	17.24	19.07	110.61
A-06	43	20.72	31.47	151.88	19	17.38	15.38	88.49	16	10.64	11.86	111.47
A-07	44	11.03	27.92	253.13	10	10.62	23.40	220.34	17	8.68	18.08	208.29
A-08	37	18.24	35.53	194.79	17	29.30	28.85	98.46	17	29.60	14.71	49.70
A-09	42	27.73	43.49	156.83	14	37.18	29.32	78.86	15	25.90	24.78	95.68
A-10	40	14.11	23.57	167.04	16	5.81	17.27	297.25	15	8.61	15.52	180.26
A-11	42	9.74	24.58	252.36	13	14.96	14.57	97.39	14	7.62	13.29	174.41
A-12	43	5.35	27.44	512.90	13	5.58	22.76	407.89	15	5.06	15.39	304.15
A-13	35	9.84	26.50	269.31	15	-0.92	19.13	2079.35	10	12.80	16.10	125.78
A-14	41	8.37	33.27	397.49	16	8.21	22.30	271.62	15	9.91	19.83	200.10
A-15	42	9.38	25.28	269.51	17	10.78	16.30	151.21	19	7.82	12.48	159.59
A-16	41	11.40	31.42	275.61	14	6.21	25.27	406.92	15	-0.28	16.33	5832.14
A-17	39	15.58	22.63	145.25	16	6.42	21.43	333.80	13	9.37	13.45	143.54
A-18	51	12.25	23.49	191.76	13	17.26	20.83	120.68	19	6.23	12.96	208.03
A-19	53	9.89	25.10	253.79	17	13.90	16.80	120.86	14	11.83	12.74	107.69
A-20	42	4.47	29.94	669.80	15	10.32	15.04	145.74	17	5.54	15.04	271.48
A-21	35	2.39	28.43	1189.54	17	5.09	18.47	362.87	14	9.83	6.45	65.62
A-22	45	7.14	27.37	383.33	13	5.08	19.78	389.37	15	6.84	14.83	216.81
A-23	43	10.57	27.54	260.55	13	4.49	21.55	479.96	15	7.80	8.96	114.87
A-24	43	4.00	23.84	596.00	17	3.43	18.11	527.99	17	5.53	6.76	122.24
A-25	38	5.88	20.90	355.44	15	5.72	11.28	197.20	15	8.31	12.42	149.46
A-26	45	-2.80	30.04	1072.86	16	-11.89	30.37	255.42	16	-12.13	21.87	180.30
A-27	42	1.49	28.90	1939.60	14	-7.15	18.39	257.20	15	9.97	13.30	133.40
A-28	36	5.89	24.88	422.41	16	4.67	19.26	412.42	17	10.10	14.52	143.76
A-29	45	15.69	33.95	216.38	18	21.11	26.12	123.73	19	17.20	16.08	93.49
A-30	47	29.27	34.25	117.01	17	21.35	23.10	108.20	19	26.17	11.59	44.29
A-31	43	25.28	38.99	154.23	20	31.64	31.40	99.24	17	26.23	24.70	94.17
A-32	42	17.34	35.99	207.55	19	23.33	23.11	99.06	18	21.44	21.09	98.37
A-33	34	14.46	28.78	199.03	17	11.76	21.14	179.76	16	13.01	11.88	91.31
A-34	32	5.69	23.56	414.06	14	7.04	20.66	293.47	20	4.89	14.79	302.45
A-37	48	1.31	22.52	1719.08	15	3.31	19.92	601.81	14	12.10	12.46	102.98
A-38	37	10.78	18.76	174.03	15	3.52	17.89	508.24	14	6.98	9.89	141.69

TABLE B-2

(continued)

AREA	NO. MEASURMNTS.	2 sec - 2 mph MEAN	2 sec - 2 mph STD DEV	2 sec - 2 mph % STD DEV	NO. MEASURMNTS.	4 sec - 1 mph MEAN	4 sec - 1 mph STD DEV	4 sec - 1 mph % STD DEV	NO. MEASURMNTS.	8 sec - 0.5 mph MEAN	8 sec - 0.5 mph STD DEV	8 sec - 0.5 mph % STD DEV
A-39	42	6.27	19.67	313.72	18	16.15	16.89	104.58	16	6.02	11.22	186.38
A-40	38	4.16	20.81	500.24	15	7.21	13.27	184.05	15	10.48	10.59	101.05
A-41	48	10.02	25.60	255.49	21	6.97	14.92	214.06	16	6.99	11.95	170.96
A-42	46	4.14	22.48	543.00	17	10.90	15.80	144.95	20	8.57	10.85	126.60
A-43	45	4.35	25.11	577.24	16	13.61	17.14	125.94	14	5.28	18.73	354.73
A-44	33	2.68	26.18	976.87	16	7.35	22.44	305.31	18	6.95	12.63	181.73
A-45	43	12.76	22.33	175.00	18	11.81	22.31	188.91	17	7.88	14.52	184.26
A-46	45	3.37	26.48	785.76	14	17.06	14.20	83.24	14	8.22	11.47	139.54
A-47	45	8.73	21.92	251.09	18	6.97	20.70	296.99	16	11.10	11.00	99.10
A-48	41	5.26	23.01	437.45	17	6.40	17.73	277.03	16	6.47	12.72	196.60
A-49	52	9.29	21.64	232.94	14	11.49	26.89	234.03	16	5.31	13.61	256.31
A-50	38	3.63	23.14	637.47	18	-2.74	16.43	599.64	13	2.08	14.09	677.40
Averages		9.88	27.28	474.14		10.57	20.19	277.88		9.71	14.29	285.78

TABLE [illegible]

URANIUM-238 (pCi/g) REPEATED PROFILE RUNS - DRUM BALING AREA

	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
AREA	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV
DB-A01	40	373.99	103.33	27.63	45	383.07	111.31	29.06	27	422.24	85.07	20.15
DB-A02	42	328.24	200.19	60.99	43	293.82	175.44	59.71	27	314.50	179.01	56.92
DB-A03	40	158.73	88.17	55.55	35	174.35	76.65	43.96	29	177.56	58.16	32.76
DB-A04	40	321.44	83.19	25.88	43	310.24	77.56	25.00	27	338.09	39.47	11.67
DB-A05	41	351.19	95.90	27.31	38	317.46	92.71	29.20	29	322.13	97.24	30.19
DB-A06	41	119.72	68.41	57.14	45	152.15	86.60	56.92	28	126.78	61.42	48.45
DB-A07	42	73.67	50.69	68.81	38	76.12	36.41	47.83	28	86.15	26.12	30.32
DB-A08	40	85.37	57.00	66.77	44	101.67	45.17	44.43	28	101.99	36.04	35.34
DB-A09	48	131.65	95.51	72.55	39	160.74	123.63	76.91	28	112.75	57.54	51.03
DB-A10	32	89.30	58.96	66.03	39	91.55	52.85	57.73	29	88.24	58.22	65.98
Averages		203.33	90.14	52.87		206.12	87.83	47.08		209.04	69.33	38.28

TABLE B-4

THORIUM-232 (pCi/g) - REPEATED PROFILE RUNS IN USID AREA

	2 sec - 2 mph			2 sec - 0.5 mph			8 sec - 0.5mph					
AREA	NO. MEASURMNTS.	MEAN	STD DEV	COUNT	NO. MEASURMNTS.	MEAN	% SD MEA	COUNT	NO. MEASURMNTS.	SD MEAN	SD MEA	COUNT
A-01	41	0.75	0.33	41	129	0.75	3.64	129	27	0.03	4.22	27
A-02	71	0.83	0.35	71	217	0.78	3.22	217	52	0.02	3.20	52
A-03	73	0.74	0.34	73	206	0.76	2.93	206	44	0.02	2.94	44
A-04	72	0.76	0.33	72	205	0.82	3.15	205	50	0.03	3.54	50
A-05	76	0.78	0.33	76	216	0.73	3.26	216	47	0.02	3.14	47
A-06	73	0.76	0.42	73	225	0.77	2.94	225	43	0.03	3.28	43
A-07	69	0.86	0.36	69	200	0.79	3.31	200	46	0.03	3.40	46
A-ROAD	52	0.35	0.34	52	120	0.43	7.43	120	28			
A-08	75	0.87	0.38	75	231	0.76	3.46	231	49	0.03	4.08	49
A-09	84	0.78	0.33	84	232	0.76	3.28	232	53	0.03	3.43	53
A-10	80	0.76	0.33	80	240	0.73	3.27	240	55	0.02	3.02	55
A-11	73	0.71	0.32	73	193	0.75	3.26	193	44	0.03	4.80	44
Averages	0.75	0.35	48.88	0.74	0.36	49.58	0.75	0.19	25.95			

TABLE B-5

THORIUM-232 (pCi/g) - REPEATED PROFILE RUNS - SOUTH FIELD

	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
AREA	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV
A-01	42	0.79	0.30	37.97	15	0.97	0.21	21.65	16	0.93	0.20	21.51
A-02	38	0.97	0.31	31.96	15	0.88	0.24	27.27	14	0.90	0.15	16.67
A-03	43	0.80	0.36	45.00	16	0.90	0.34	37.78	17	1.09	0.34	31.19
A-04	44	1.73	0.76	43.93	17	2.22	0.76	34.23	15	1.92	0.56	29.17
A-05	42	1.69	0.87	51.48	17	1.52	0.77	50.66	16	1.30	0.52	40.00
A-06	43	1.02	0.41	40.20	19	0.94	0.24	25.53	16	0.96	0.22	22.92
A-07	44	1.00	0.35	35.00	10	0.96	0.35	36.46	17	1.16	0.32	27.59
A-08	37	1.50	0.54	36.00	17	2.18	0.46	21.10	17	1.97	0.51	25.89
A-09	42	2.53	0.86	33.99	14	3.50	0.50	14.29	15	2.71	0.61	22.51
A-10	40	1.42	0.70	49.30	16	1.00	0.39	39.00	15	1.02	0.46	45.10
A-11	42	0.74	0.30	40.54	13	0.72	0.26	36.11	14	0.71	0.14	19.72
A-12	43	0.69	0.36	52.17	13	0.75	0.34	45.33	15	0.77	0.11	14.29
A-13	35	0.87	0.37	42.53	15	0.84	0.38	45.24	10	0.72	0.17	23.61
A-14	41	0.98	0.50	51.02	16	0.75	0.37	49.33	15	0.78	0.20	25.64
A-15	42	0.70	0.33	47.14	17	0.70	0.22	31.43	19	0.73	0.20	27.40
A-16	41	0.65	0.33	50.77	14	0.63	0.17	26.98	15	0.68	0.16	23.53
A-17	39	0.65	0.33	50.77	16	0.68	0.24	35.29	13	0.63	0.15	23.81
A-18	51	0.63	0.28	44.44	13	0.61	0.27	44.26	19	0.65	0.16	24.62
A-19	53	0.58	0.35	60.34	17	0.69	0.24	34.78	14	0.62	0.15	24.19
A-20	42	0.69	0.35	50.72	15	0.66	0.23	34.85	17	0.62	0.15	24.19
A-21	35	0.74	0.36	48.65	17	0.75	0.20	26.67	14	0.67	0.16	23.88
A-22	45	0.60	0.28	46.67	13	0.53	0.20	37.74	15	0.51	0.12	23.53
A-23	43	0.59	0.29	49.15	13	0.60	0.19	31.67	15	0.66	0.16	24.24
A-24	43	0.57	0.26	45.61	17	0.59	0.19	32.20	17	0.53	0.16	30.19
A-25	38	0.50	0.30	60.00	15	0.52	0.24	46.15	15	0.52	0.19	36.54
A-26	45	0.96	0.59	61.46	16	1.09	0.62	56.88	16	1.46	0.47	32.19
A-27	42	0.78	0.42	53.85	14	0.87	0.43	49.43	15	0.71	0.20	28.17
A-28	36	0.65	0.24	36.92	16	0.60	0.27	45.00	17	0.65	0.15	23.08
A-29	45	0.67	0.36	53.73	18	0.67	0.27	40.30	19	0.69	0.17	24.64
A-30	47	0.74	0.43	58.11	17	0.69	0.38	55.07	19	0.96	0.23	23.96
A-31	43	1.09	0.58	53.21	20	1.21	0.34	28.10	17	1.11	0.26	23.42

TABLE B-5

(continued)

		2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph		
AREA	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV
A-32	42	1.03	0.42	40.78	19	1.00	0.42	42.00	18	0.96	0.25	26.04
A-33	34	0.88	0.40	45.45	17	0.83	0.25	30.12	16	0.76	0.24	31.58
A-34	38	0.75	0.29	38.67	14	0.68	0.28	41.18	20	0.60	0.16	26.67
A-37	48	0.61	0.29	47.54	15	0.53	0.33	62.26	14	0.53	0.12	22.64
A-38	37	0.54	0.29	53.70	15	0.64	0.18	28.13	14	0.54	0.12	22.22
A-39	42	0.51	0.32	62.75	18	0.60	0.17	28.33	16	0.54	0.11	20.37
A-40	38	0.62	0.26	41.94	15	0.61	0.22	36.07	15	0.51	0.18	35.29
A-41	48	0.53	0.28	52.83	21	0.50	0.23	46.00	16	0.59	0.15	25.42
A-42	46	0.47	0.36	76.60	17	0.43	0.21	48.84	20	0.47	0.16	34.04
A-43	45	0.62	0.40	64.52	16	0.66	0.12	18.18	14	0.64	0.20	31.25
A-44	33	0.69	0.35	50.72	16	0.77	0.32	41.56	18	0.73	0.19	26.03
A-45	43	0.72	0.34	47.22	18	0.64	0.26	40.63	17	0.67	0.11	16.42
A-46	45	0.63	0.32	50.79	14	0.65	0.23	35.38	14	0.59	0.17	28.81
A-47	45	0.60	0.27	45.00	18	0.68	0.22	32.35	16	0.59	0.13	22.03
A-48	41	0.45	0.34	75.56	17	0.50	0.16	32.00	16	0.59	0.16	27.12
A-49	52	0.54	0.35	64.81	14	0.41	0.25	60.98	16	0.55	0.12	21.82
A-50	38	0.55	0.31	56.36	18	0.72	0.28	38.89	13	0.72	0.21	29.17
Averages		0.82	0.39	49.54		0.86	0.30	37.58		0.83	0.22	26.13

TAB[illegible]6

THORIUM-232 (pCi/g) REPEATED PROFILE RUNS - DRUM BALING AREA

	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
AREA	**NO. MEASURMNTS.**	**MEAN**	**STD DEV**	**% STD DEV**	**NO. MEASURMNTS.**	**MEAN**	**STD DEV**	**% STD DEV**	**NO. MEASURMNTS.**	**MEAN**	**STD DEV**	**% STD DEV**
DB-A01	40	3.21	0.99	30.84	45	3.02	1.16	38.41	27	3.45	0.57	16.52
DB-A02	42	2.99	1.04	34.78	43	2.99	1.06	35.45	27	2.95	0.59	20.00
DB-A03	40	2.81	0.82	29.18	35	2.76	0.73	26.45	29	2.87	0.62	21.60
DB-A04	40	3.98	0.86	21.61	43	3.69	0.71	19.24	27	3.69	0.40	10.84
DB-A05	41	3.79	1.07	28.23	38	3.85	0.79	20.52	29	3.87	0.65	16.80
DB-A06	41	2.31	0.73	31.60	45	2.35	0.60	25.53	28	2.26	0.62	27.43
DB-A07	42	2.10	0.60	28.57	38	2.21	0.53	23.98	28	2.25	0.49	21.78
DB-A08	40	3.82	1.22	31.94	44	4.15	1.19	28.67	28	4.31	1.27	29.47
DB-A09	48	6.83	2.63	38.51	39	7.98	3.24	40.60	28	6.35	1.57	24.72
DB-A10	32	5.77	1.07	18.54	39	5.85	1.43	24.44	29	6.26	1.02	16.29
Averages		3.76	1.10	29.38		3.89	1.14	28.33		3.83	0.78	20.55

TABLE B-7

RADIUM-26 (pCi/g) - REPEATED PROFILE RUNS IN USID AREA

	2 SEC - 2 MPH			2 SEC - 0.5 MPH			8 SEC - 0.5 MPH					
AREA	NO. MEASURMNTS.	MEAN	STD DEV	COUNT	NO. MEASURMNTS.	MEAN	% SD MEAN	COUNT	NO. MEASURMNTS.	SD MEAN	SD MEA	COUNT
A-01	41	0.76	0.82	41	129	0.7	9.94	129	27	0.07	9.36	27
A-02	71	0.61	0.75	71	217	0.8	6.79	217	52	0.06	7.68	52
A-03	73	0.80	0.73	73	206	0.86	6.00	206	44	0.07	8.96	44
A-04	72	0.76	0.82	72	205	0.73	7.94	205	50	0.06	7.16	50
A-05	76	0.78	0.86	76	216	0.86	6.65	216	47	0.05	6.33	47
A-06	73	0.79	0.87	73	225	0.75	7.20	225	43	0.06	6.46	43
A-07	69	0.77	0.7	69	200	0.81	7.33	200	46	0.05	5.61	46
A-ROAD	52	0.69	0.68	52	120	0.62	9.86	120	28			
A-08	75	0.78	0.84	75	231	0.85	7.12	231	49	0.07	7.97	49
A-09	84	0.96	0.62	84	232	0.94	5.52	232	53	0.05	6.29	53
A-10	80	0.88	0.78	80	240	0.78	6.21	240	55	0.06	6.44	55
A-11	73	0.68	0.71	73	193	0.77	7.29	193	44	0.06	9.19	44
Averages	0.77	0.77	100.43	0.79	0.80	101.65	0.81	0.40	50.16			

TABLE B-8

RADIUM-226 (pCi/g) - REPEATED PROFILE RUNS - SOUTH FIELD

	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
AREA	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV
A-01	42	1.05	0.81	77.14	15	1.23	0.49	39.84	16	1.01	0.37	36.63
A-02	38	0.88	0.91	103.41	15	1.12	0.48	42.86	14	1.10	0.41	37.27
A-03	43	1.16	1.00	86.21	16	1.18	0.44	37.29	17	1.12	0.49	43.75
A-04	44	0.80	1.23	153.75	17	0.90	0.98	108.89	15	0.63	0.43	68.25
A-05	42	0.93	0.98	105.38	17	1.01	0.68	67.33	16	1.27	0.59	46.46
A-06	43	1.09	0.86	78.90	19	1.39	0.66	47.48	16	1.23	0.36	29.27
A-07	44	1.02	0.83	81.37	10	1.43	0.35	24.48	17	0.82	0.33	40.24
A-08	37	0.71	1.08	152.11	17	0.81	0.83	102.47	17	0.49	0.54	110.20
A-09	42	0.64	1.20	187.50	14	0.39	0.95	243.59	15	0.47	0.70	148.94
A-10	40	0.48	0.99	206.25	16	0.96	0.74	77.08	15	0.90	0.48	53.33
A-11	42	1.04	0.65	62.50	13	0.85	0.35	41.18	14	0.97	0.39	40.21
A-12	43	0.95	0.69	72.63	13	1.09	0.67	61.47	15	0.95	0.41	43.16
A-13	35	1.33	0.67	50.38	15	0.96	0.68	70.83	10	0.90	0.28	31.11
A-14	41	1.38	0.95	68.84	16	1.28	0.72	56.25	15	1.62	0.51	31.48
A-15	42	1.38	0.73	52.90	17	1.56	0.50	32.05	19	1.38	0.34	24.64
A-16	41	1.23	0.91	73.98	14	1.21	0.63	52.07	15	1.03	0.37	35.92
A-17	39	1.22	0.66	54.10	16	1.28	0.45	35.16	13	1.22	0.38	31.15
A-18	51	1.07	0.79	73.83	13	1.10	0.57	51.82	19	1.07	0.54	50.47
A-19	53	0.98	0.87	88.78	17	1.05	0.54	51.43	14	1.24	0.46	37.10
A-20	42	0.99	0.84	84.85	15	1.08	0.44	40.74	17	0.91	0.36	39.56
A-21	35	1.06	0.75	70.75	17	1.22	0.47	38.52	14	0.93	0.37	39.78
A-22	45	0.94	0.85	90.43	13	1.24	0.82	66.13	15	1.08	0.40	37.04
A-23	43	1.17	0.78	66.67	13	1.02	0.42	41.18	15	1.11	0.42	37.84
A-24	43	1.02	0.83	81.37	17	1.08	0.76	70.37	17	0.96	0.23	23.96
A-25	38	0.95	0.74	77.89	15	0.88	0.58	65.91	15	1.09	0.45	41.28
A-26	45	1.20	0.82	68.33	16	0.75	0.90	120.00	16	1.50	0.52	34.67
A-27	42	1.47	0.95	64.63	14	1.44	0.38	26.39	15	1.50	0.36	24.00
A-28	36	1.70	1.04	61.18	16	1.69	0.67	39.64	17	1.65	0.35	21.21
A-29	45	2.94	1.55	52.72	18	2.89	1.75	60.55	19	3.02	1.11	36.75
A-30	47	4.30	1.50	34.88	17	3.72	1.07	28.76	19	5.27	1.65	31.31
A-31	43	5.75	1.79	31.13	20	6.30	1.39	22.06	17	6.48	0.68	10.49

TABLE B-8

(continued)

AREA	2 sec - 2 mph NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	4 sec - 1 mph NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	8 sec - 0.5 mph NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV
A-32	42	4.53	1.42	31.35	19	4.20	1.94	46.19	18	4.20	0.84	20.00
A-33	34	2.94	1.35	45.92	17	2.89	0.89	30.80	16	2.51	0.76	30.28
A-34	38	1.69	1.05	62.13	14	1.47	0.57	38.78	20	1.40	0.39	27.86
A-37	48	0.70	0.72	102.86	15	0.75	0.62	82.67	14	0.92	0.46	50.00
A-38	37	0.61	0.74	121.31	15	0.96	0.45	46.88	14	0.78	0.39	50.00
A-39	42	0.67	0.82	122.39	18	0.96	0.66	68.75	16	0.95	0.36	37.89
A-40	38	0.86	0.74	86.05	15	1.01	0.50	49.50	15	1.09	0.23	21.10
A-41	48	1.29	0.79	61.24	21	0.91	0.61	67.03	16	0.91	0.38	41.76
A-42	46	1.06	0.65	61.32	17	1.15	0.61	53.04	20	1.10	0.31	28.18
A-43	45	0.98	0.76	77.55	16	0.94	0.56	59.57	14	0.98	0.31	31.63
A-44	33	0.80	0.85	106.25	16	0.89	0.51	57.30	18	0.88	0.43	48.86
A-45	43	1.24	0.68	54.84	18	0.98	0.64	65.31	17	0.82	0.35	42.68
A-46	45	1.04	0.71	68.27	14	1.26	0.51	40.48	14	0.99	0.39	39.39
A-47	45	0.99	1.00	101.01	18	1.00	0.43	43.00	16	1.15	0.31	26.96
A-48	41	1.07	0.68	63.55	17	1.18	0.53	44.92	16	1.15	0.32	27.83
A-49	52	1.16	0.81	69.83	14	1.03	0.46	44.66	16	0.87	0.52	59.77
A-50	38	0.82	0.73	89.02	18	0.92	0.48	52.17	13	0.80	0.47	58.75
Averages		1.36	0.91	82.08		1.39	0.67	57.39		1.38	0.47	40.84

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TABLE

RADIUM-226 (pCi/g) REPEATED PROFILE RUNS - DRUM BALING AREA

	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
AREA	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV
DB-A01	40	17.15	4.02	23.44	45	16.23	3.22	19.84	27	17.16	2.43	14.16
DB-A02	42	13.45	7.20	53.53	43	11.45	5.10	44.54	27	12.05	5.24	43.49
DB-A03	40	8.70	3.54	40.69	35	9.19	3.36	36.56	29	9.55	3.41	35.71
DB-A04	40	16.72	3.69	22.07	43	15.91	3.20	20.11	27	15.81	2.59	16.38
DB-A05	41	14.58	3.96	27.16	38	14.08	4.09	29.05	29	14.24	4.22	29.63
DB-A06	41	5.05	2.24	44.36	45	5.67	2.69	47.44	28	5.04	2.28	45.24
DB-A07	42	3.10	1.56	50.32	38	3.19	1.07	33.54	28	3.68	0.85	23.10
DB-A08	40	2.44	1.79	73.36	44	2.77	1.16	41.88	28	2.54	0.78	30.71
DB-A09	48	2.06	2.12	102.91	39	2.30	1.43	62.17	28	1.93	1.20	62.18
DB-A10	32	3.57	2.02	56.58	39	3.00	1.43	47.67	29	2.59	1.36	52.51
Averages		8.68	3.21	49.44		8.38	2.68	38.28		8.46	2.44	35.31

TABLE B-10

TOTAL ACTIVITY (CPS) - REPEATED PROFILE RUNS IN USID AREA

	2 sec - 2 mph			2 sec - 0.5 mph				8 sec - 0.5 mph				
AREA	NO. MEASURMNTS.	MEAN (CPS)	D DEV (CNT	NO. MEASURMNTS.	MEAN	STD DEV	COUNT	NO. MEASURMNTS.	MEAN (CPS)	SD MEAN	SD MEA	COUNT
A-01	41	2781.26	226.20	129	5544.43	142.50	129	27	2813.86	182.32	0.81	27
A-02	71	2926.83	124.05	217	5863.31	66.24	217	52	2954.16	71.87	0.30	52
A-03	73	2964.07	129.49	206	5892.92	64.29	206	44	2969.10	63.77	0.27	44
A-04	72	3034.49	132.82	205	6053.41	68.54	205	50	3043.23	63.91	0.26	50
A-05	76	3089.30	142.48	216	6152.60	72.64	216	47	3102.44	73.72	0.30	47
A-06	73	3035.76	153.38	225	6055.38	71.73	225	43	3060.92	75.83	0.31	43
A-07	69	3097.12	374.49	200	6201.68	120.09	200	46	3025.28	305.38	1.26	46
A-ROAD	52	2075.35	959.49	120	4015.78	524.35	120	28	2307.47			
A-08	75	3140.69	603.07	231	6099.38	430.32	231	49	3028.87	538.65	2.22	49
A-09	84	3183.90	158.29	232	6384.64	75.59	232	53	3210.17	71.12	0.28	53
A-10	80	3065.56	243.83	240	6168.30	111.38	240	55	3118.10	147.57	0.59	55
A-11	73	2850.26	168.62	193	5735.02	79.06	193	44	2838.33	240.22	1.06	44
Averages	2937.05	142.34	5.30	2923.62	152.23	5.78	2955.99	176.44	6.36			

TABLE B-11

TOTAL ACTIVITY (CPS) - REPEATED PROFILE RUNS - SOUTH FIELD

	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
AREA	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV
A-01	42	2628.14	136.69	5.20	15	2768.40	162.85	5.88	16	2751.01	114.78	4.17
A-02	38	2886.04	85.21	2.95	15	2935.32	64.10	2.18	14	2942.71	49.32	1.68
A-03	43	3017.47	129.37	4.29	16	3192.61	126.84	3.97	17	3218.07	170.01	5.28
A-04	44	3710.57	544.22	14.67	17	4106.04	516.68	12.58	15	3959.26	622.55	15.72
A-05	42	3726.29	639.01	17.15	17	3491.99	621.71	17.80	16	3297.55	541.65	16.43
A-06	43	3158.94	137.30	4.35	19	3065.26	127.52	4.16	16	2979.40	126.98	4.26
A-07	44	2826.91	137.14	4.85	10	2829.38	78.76	2.78	17	2958.47	203.45	6.88
A-08	37	3178.31	201.28	6.33	17	3762.81	445.79	11.85	17	3745.56	402.00	10.73
A-09	42	4107.85	653.62	15.91	14	5078.32	307.34	6.05	15	4586.56	480.05	10.47
A-10	40	3169.19	755.65	23.84	16	2899.78	378.93	13.07	15	2870.53	436.31	15.20
A-11	42	2540.73	58.76	2.31	13	2554.10	41.39	1.62	14	2562.29	35.19	1.37
A-12	43	2533.90	99.59	3.93	13	2558.35	49.34	1.93	15	2560.64	32.62	1.27
A-13	35	2756.94	207.17	7.51	15	2695.93	119.13	4.42	10	2636.15	130.37	4.95
A-14	41	2988.33	145.58	4.87	16	2975.88	104.60	3.51	15	2884.16	120.29	4.17
A-15	42	2664.61	121.09	4.54	17	2675.09	88.96	3.33	19	2639.94	113.52	4.30
A-16	41	2546.12	42.38	1.66	14	2585.66	25.31	0.98	15	2566.31	20.95	0.82
A-17	39	2521.17	48.80	1.94	16	2538.91	43.69	1.72	13	2540.38	35.65	1.40
A-18	51	2526.23	76.45	3.03	13	2538.60	74.68	2.94	19	2538.55	81.30	3.20
A-19	53	2412.09	61.70	2.56	17	2398.68	41.71	1.74	14	2449.26	35.78	1.46
A-20	42	2486.77	61.40	2.47	15	2502.18	65.59	2.62	17	2542.66	85.73	3.37
A-21	35	2663.60	60.49	2.27	17	2658.35	71.87	2.70	14	2638.17	70.99	2.69
A-22	45	2359.81	142.85	6.05	13	2334.08	76.22	3.27	15	2318.43	43.73	1.89
A-23	43	2401.81	76.30	3.18	13	2419.60	65.25	2.70	15	2424.02	40.00	1.65
A-24	43	2277.48	113.52	4.98	17	2316.32	105.32	4.55	17	2226.23	99.85	4.49
A-25	38	2162.83	151.71	7.01	15	2202.70	161.34	7.32	15	2324.09	164.87	7.09
A-26	45	2921.77	490.38	16.78	16	3134.81	610.87	19.49	16	3444.35	412.10	11.96
A-27	42	2803.29	356.89	12.73	14	2926.16	394.05	13.47	15	2767.81	208.18	7.52
A-28	36	2731.35	170.51	6.24	16	2784.13	133.32	4.79	17	2874.38	122.42	4.26
A-29	45	3621.93	587.57	16.22	18	3496.76	639.16	18.28	19	3683.53	508.71	13.81
A-30	47	4881.83	632.49	12.96	17	4603.65	584.16	12.69	19	5292.45	945.46	17.86
A-31	43	6076.42	250.96	4.13	20	6365.26	276.89	4.35	17	6329.93	404.82	6.40

TABLE B-11

(continued)

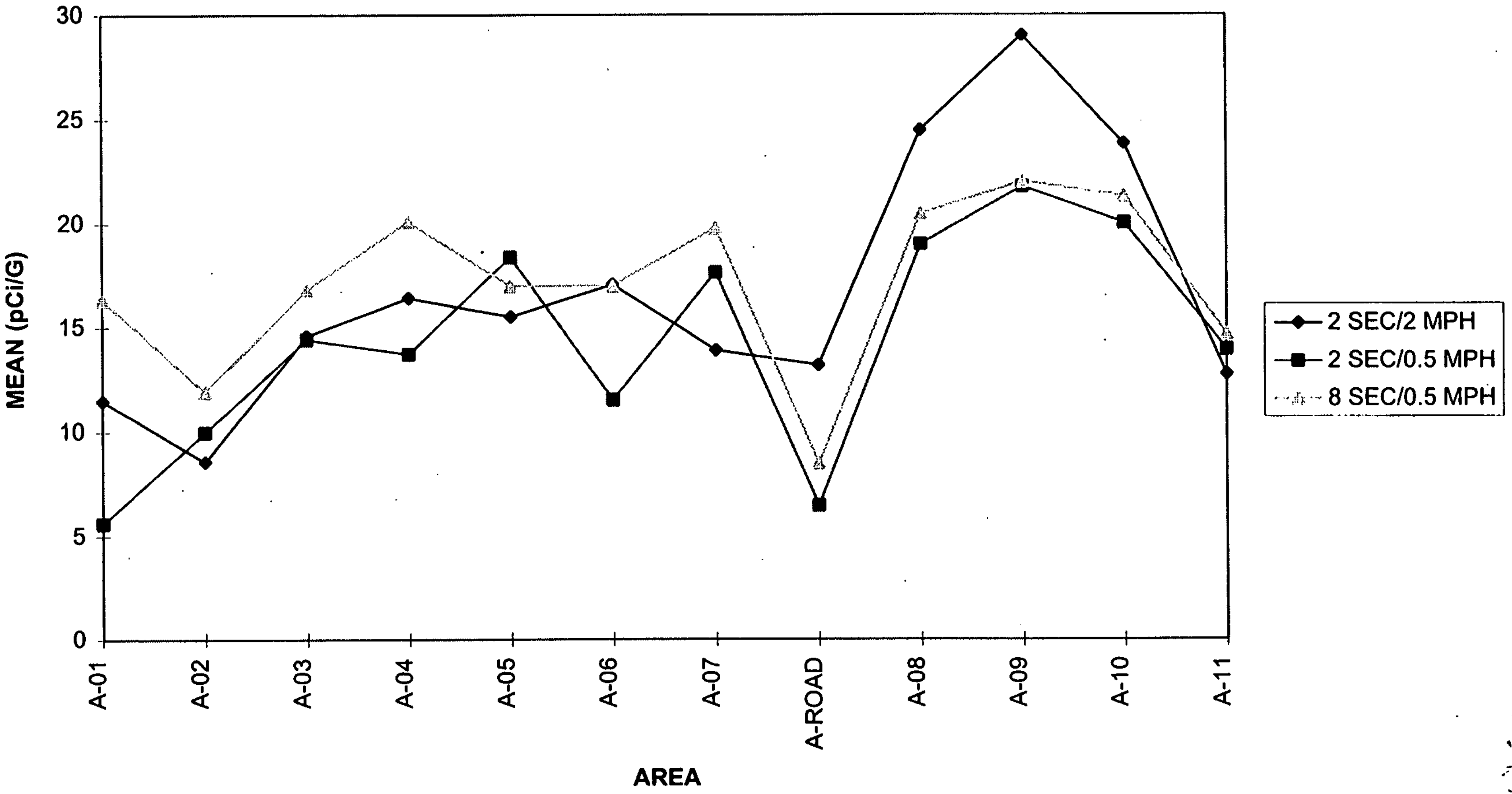
		2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph		
AREA	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV
A-32	42	5026.76	331.15	6.59	19	4721.18	1045.58	22.15	18	4665.24	524.55	11.24
A-33	34	3814.10	521.72	13.68	17	3631.47	489.34	13.48	16	3352.57	350.93	10.47
A-34	38	2927.86	182.13	6.22	14	2930.64	173.93	5.93	20	2810.93	206.47	7.35
A-37	48	2243.93	74.91	3.34	15	2279.65	78.89	3.46	14	2206.01	57.16	2.59
A-38	37	2118.85	32.12	1.52	15	2160.17	29.03	1.34	14	2158.10	25.84	1.20
A-39	42	2172.04	40.49	1.86	18	2200.21	36.80	1.67	16	2217.81	24.47	1.10
A-40	38	2237.45	142.73	6.38	15	2229.12	24.23	1.09	15	2216.87	22.06	1.00
A-41	48	2159.66	49.90	2.31	21	2217.67	114.42	5.16	16	2167.01	42.95	1.98
A-42	46	2060.37	72.94	3.54	17	2070.99	119.78	5.78	20	2060.31	57.89	2.81
A-43	45	2238.98	227.54	10.16	16	2294.80	182.05	7.93	14	2359.67	139.60	5.92
A-44	33	2516.55	52.08	2.07	16	2553.73	27.83	1.09	18	2557.17	34.92	1.37
A-45	43	2554.52	44.04	1.72	18	2575.18	42.39	1.65	17	2549.51	42.23	1.66
A-46	45	2460.80	59.47	2.42	14	2461.43	50.79	2.06	14	2432.74	46.50	1.91
A-47	45	2334.78	46.27	1.98	18	2331.99	34.98	1.50	16	2315.73	34.78	1.50
A-48	41	2196.40	96.71	4.40	17	2206.32	69.52	3.15	16	2200.21	41.62	1.89
A-49	52	2152.91	39.78	1.85	14	2201.98	28.98	1.32	16	2187.17	31.77	1.45
A-50	38	2254.30	111.39	4.94	18	2407.15	134.86	5.60	13	2398.31	98.19	4.09
Averages		197.95	6.29	2893.10	193.47	5.90	2883.50	180.03	5.34			

TABL[illegible]2

TOTAL ACTIVITY (CPS) - REPEATED PROFILE RUNS - DRUM BALING AREA

	2 sec - 2 mph				4 sec - 1 mph				8 sec - 0.5 mph			
AREA	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV	NO. MEASURMNTS.	MEAN	STD DEV	% STD DEV
DB-A01	40	24548.21	2550.22	10.39	45	24495.21	2953.34	12.06	27	24433.30	2020.16	8.27
DB-A02	42	19840.57	5893.34	29.70	43	19010.63	5825.21	30.64	27	19477.18	6422.73	32.98
DB-A03	40	14610.55	2729.11	18.68	35	14961.60	2311.94	15.45	29	15485.49	2363.50	15.26
DB-A04	40	20707.99	1532.91	7.40	43	20913.29	1496.68	7.16	27	20820.33	1259.25	6.05
DB-A05	41	20531.66	2336.67	11.38	38	20359.53	3152.36	15.48	29	19905.35	3356.46	16.86
DB-A06	41	11892.34	2153.04	18.10	45	12502.35	3059.79	24.47	28	11741.16	3035.52	25.85
DB-A07	42	9443.32	800.80	8.48	38	9458.07	815.47	8.62	28	9901.23	1061.36	10.72
DB-A08	40	10484.69	626.36	5.97	44	10662.81	656.33	6.16	28	10652.36	542.83	5.10
DB-A09	48	12572.71	1936.28	15.40	39	13374.39	2896.54	21.66	28	12287.36	1490.64	12.13
DB-A10	32	12029.48	908.24	7.55	39	12222.88	1037.56	8.49	29	12335.19	1430.15	11.59
Averages		15666.15	2146.70	13.31		15796.08	2420.52	15.02		15703.90	2298.26	14.48

FIGURE B-1
URANIUM - 238 - USID AREA - MEAN



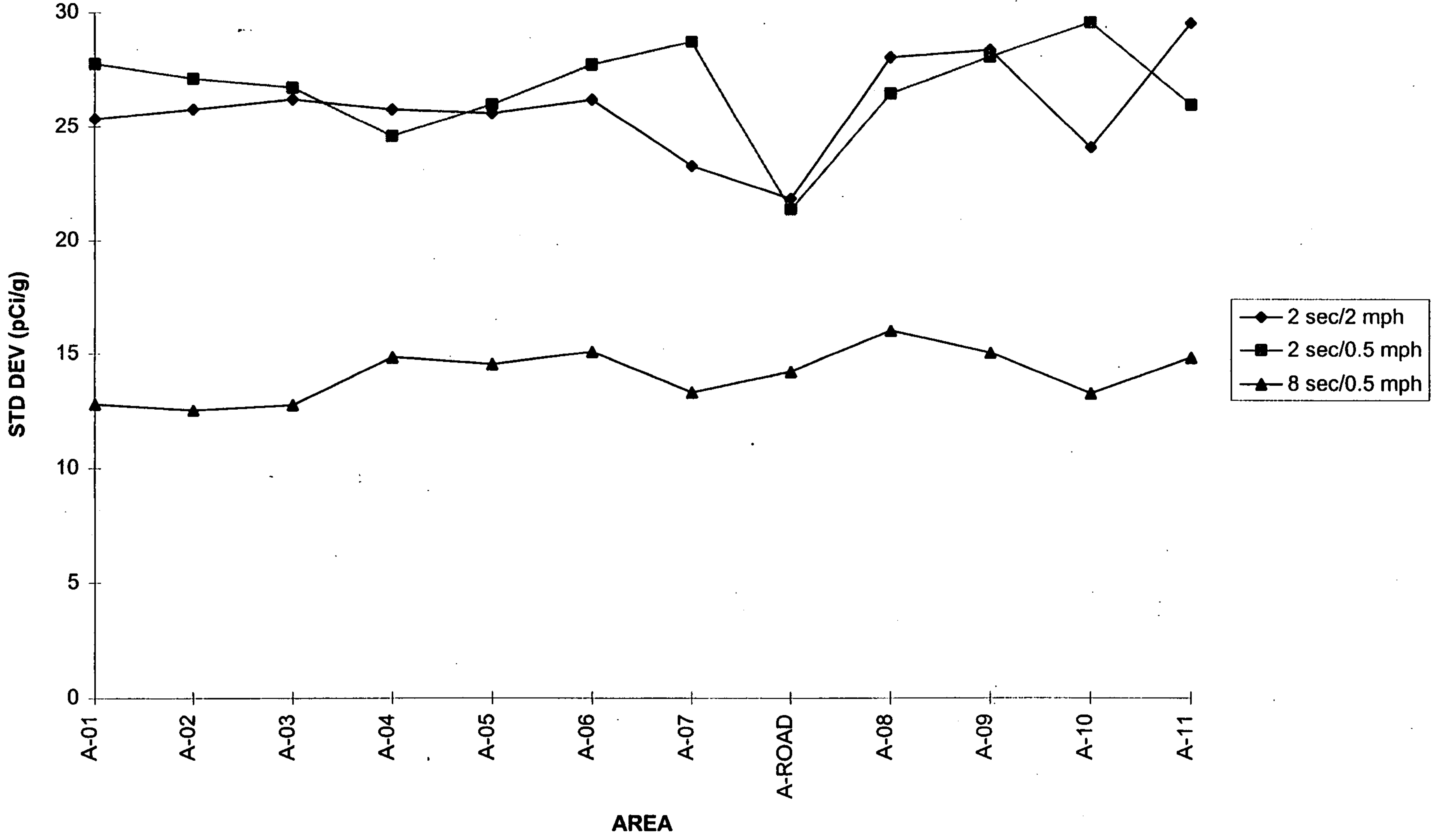


FIGURE B-2
URANIUM-238 - USID AREA - STANDARD DEVIATION

FIGURE B-3
URANIUM-238 - USID AREA - % STANDARD DEVIATION

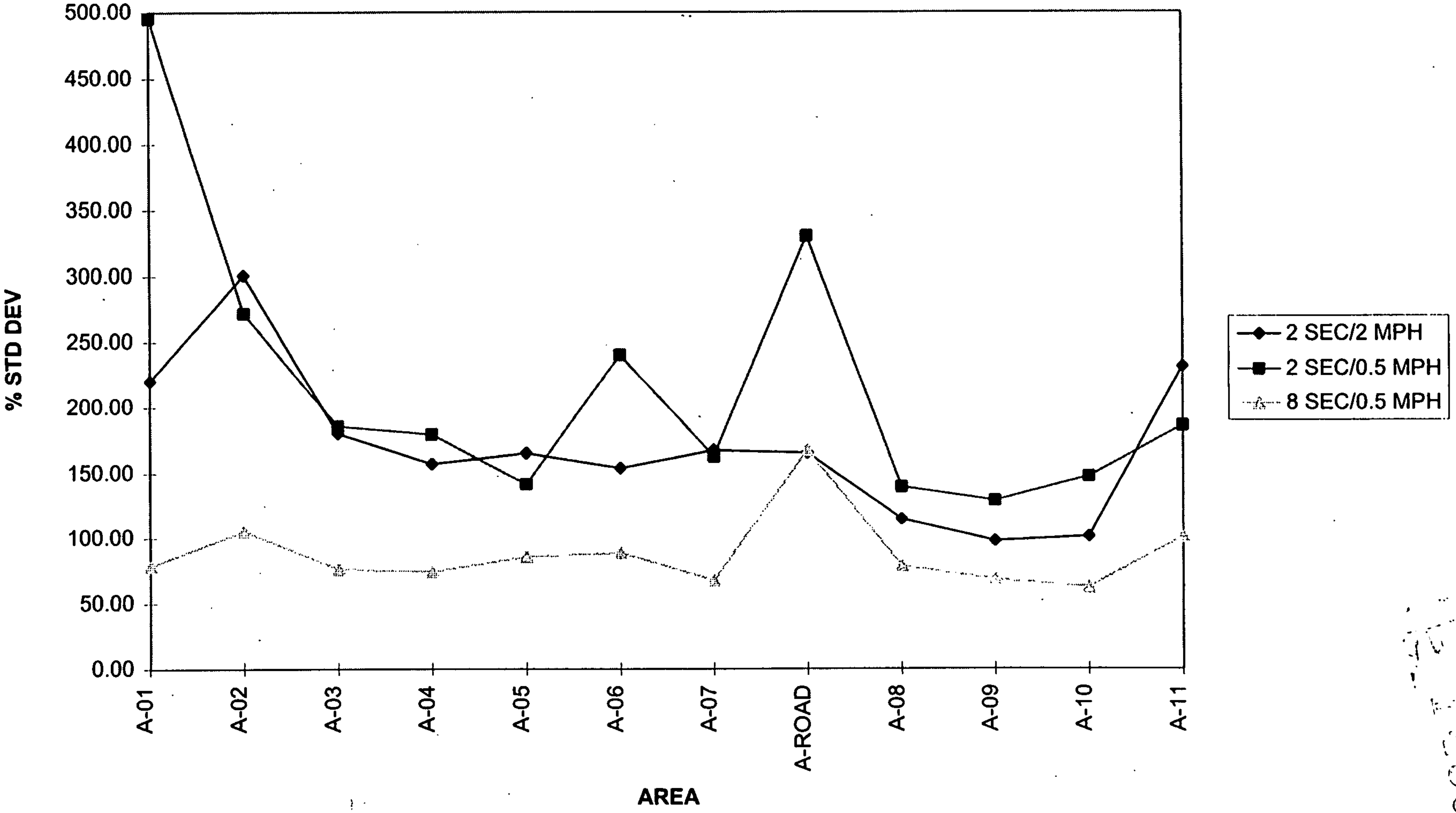


FIGURE B-4
URANIUM-238 - SOUTH FIELD - MEAN

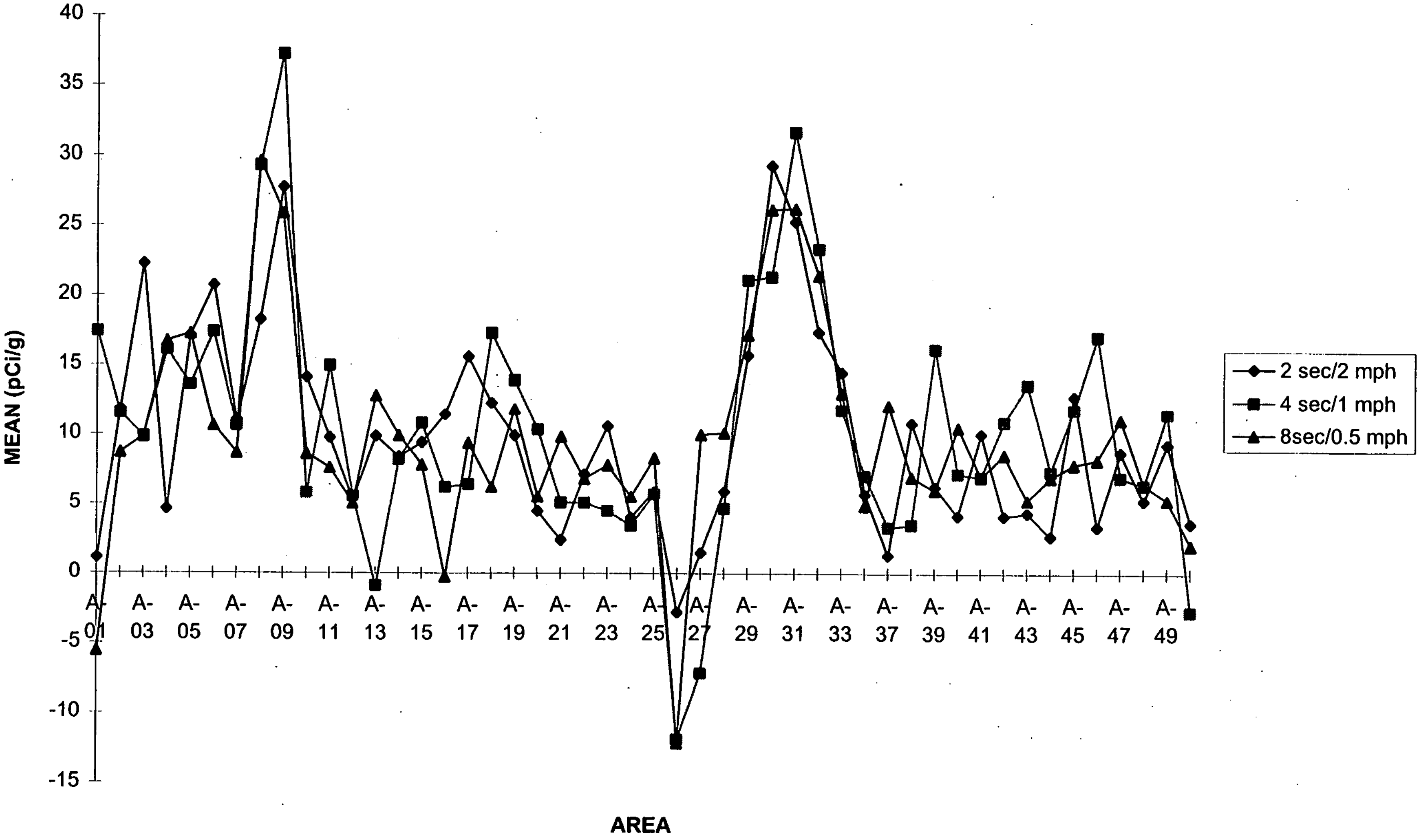


FIGURE B-5
URANIUM-238 SOUTH FIELD - STANDARD DEVIATION

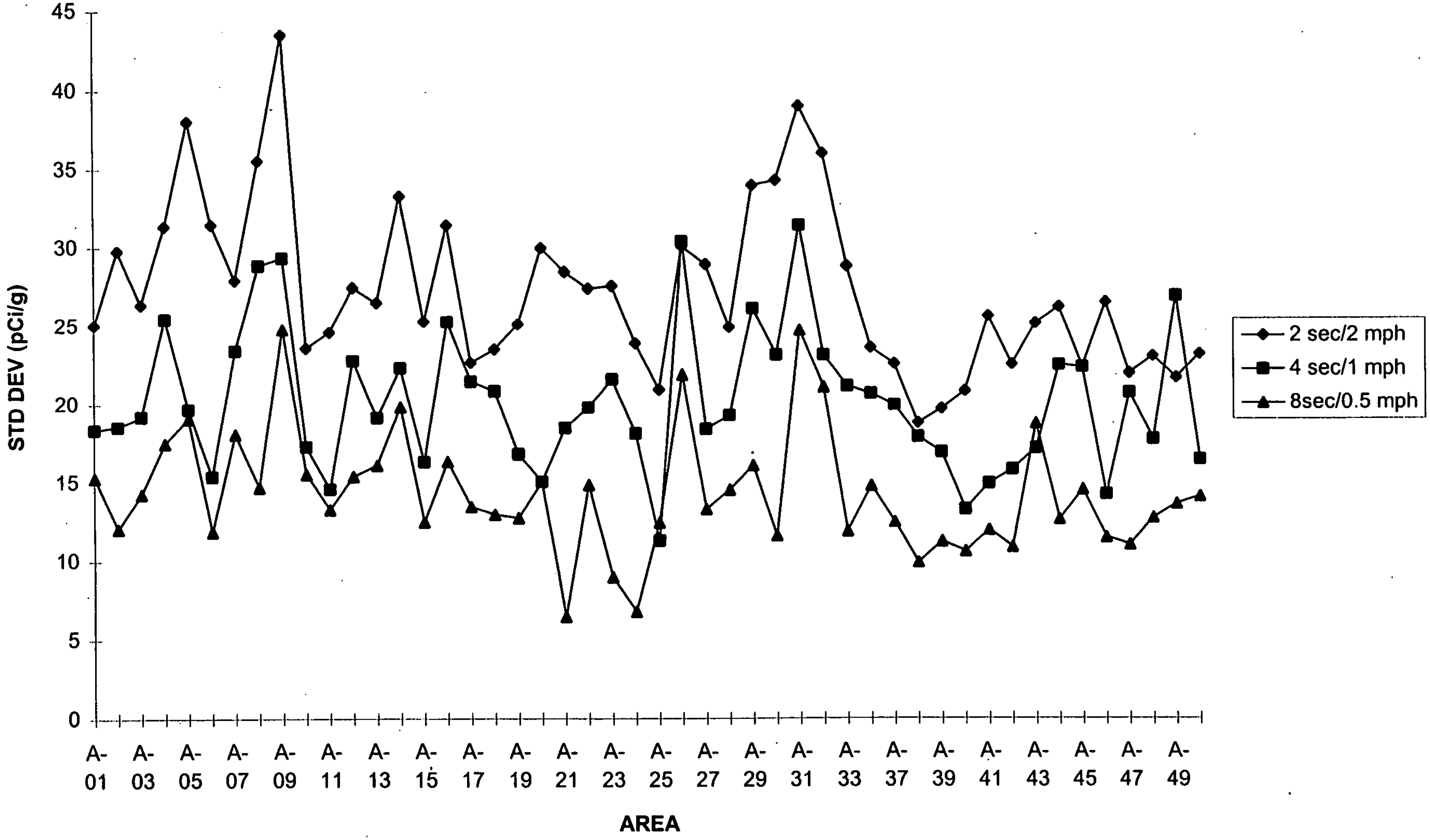


FIGURE B-6
URANIUM-238 - SOUTH FIELD - % STANDARD DEVIATION

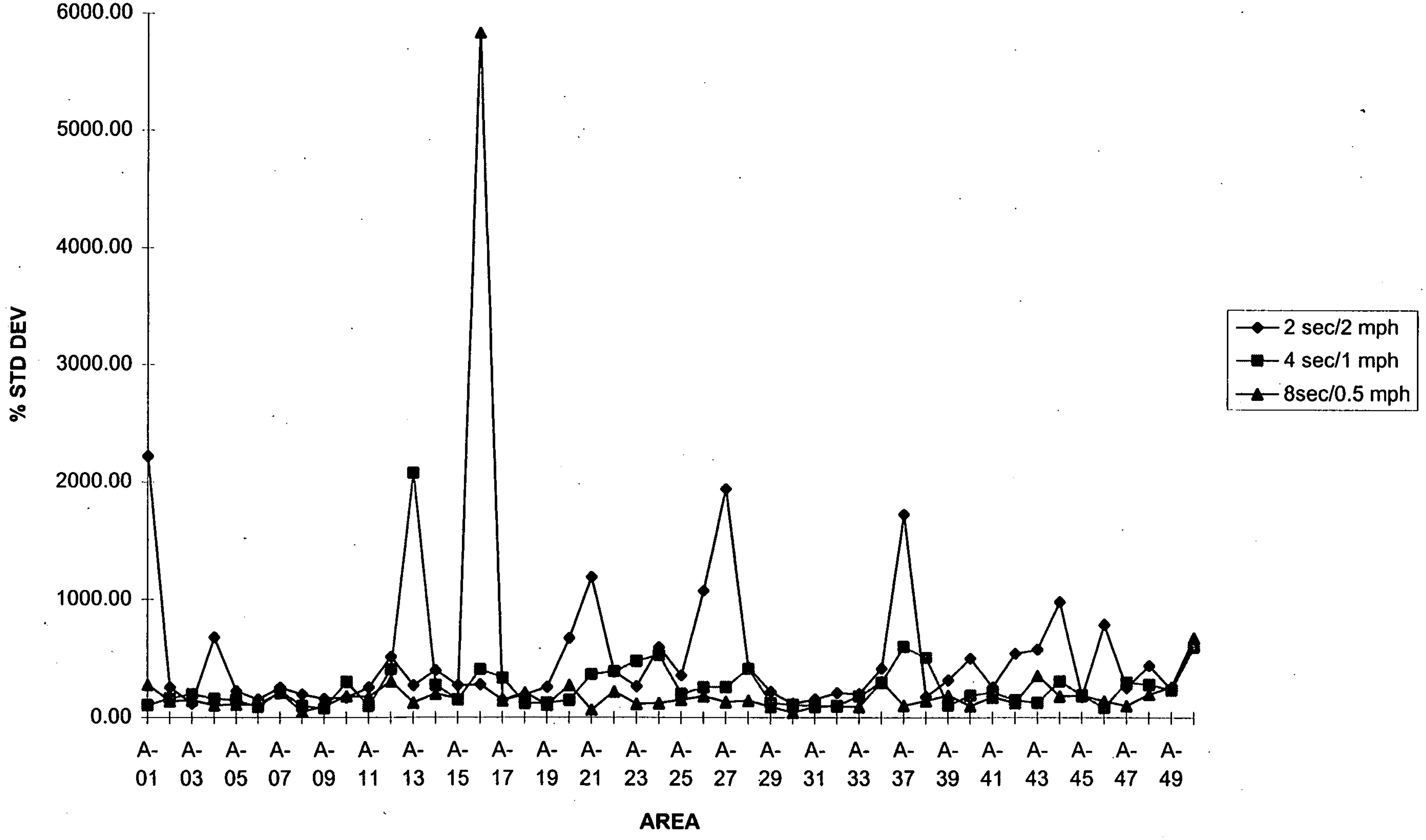


FIGURE B-7
URANIUM-238 DRUM BALING AREA - MEAN

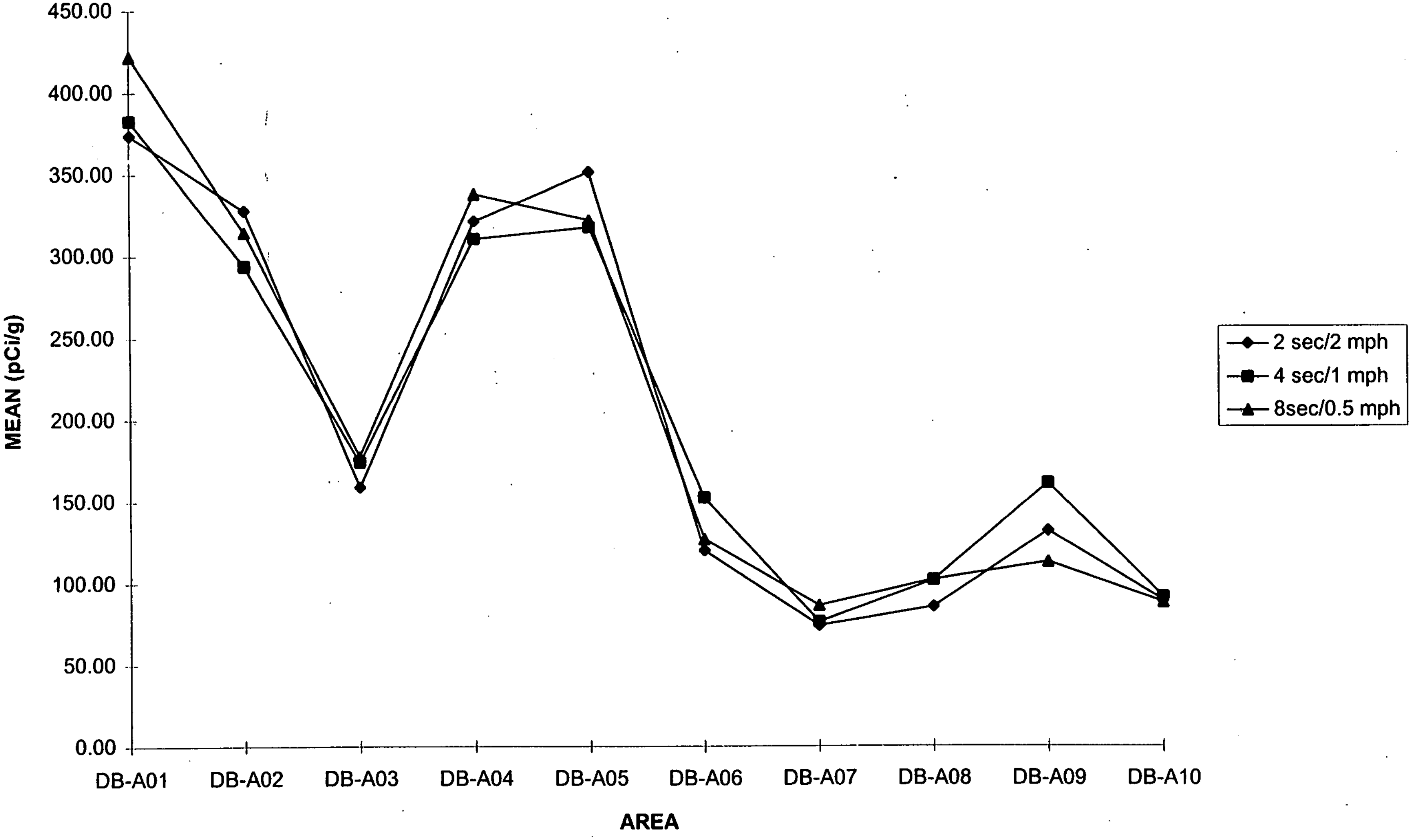


FIGURE B-8
URANIUM-238 DRUM BALING AREA - STANDARD DEVIATION

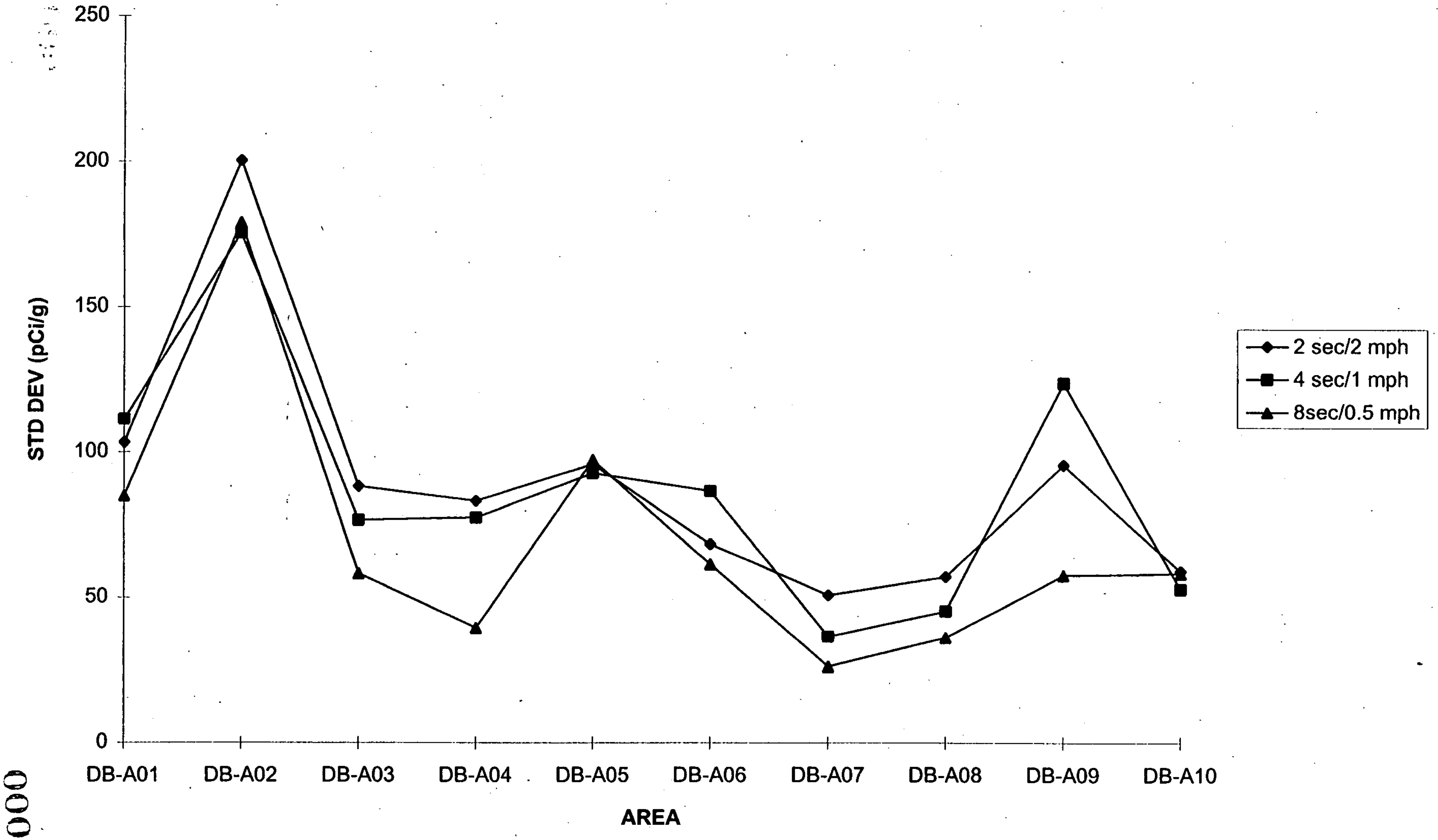


FIGURE B-9
URANIUM-238 DRUM BALING AREA - % STANDARD DEVIATION

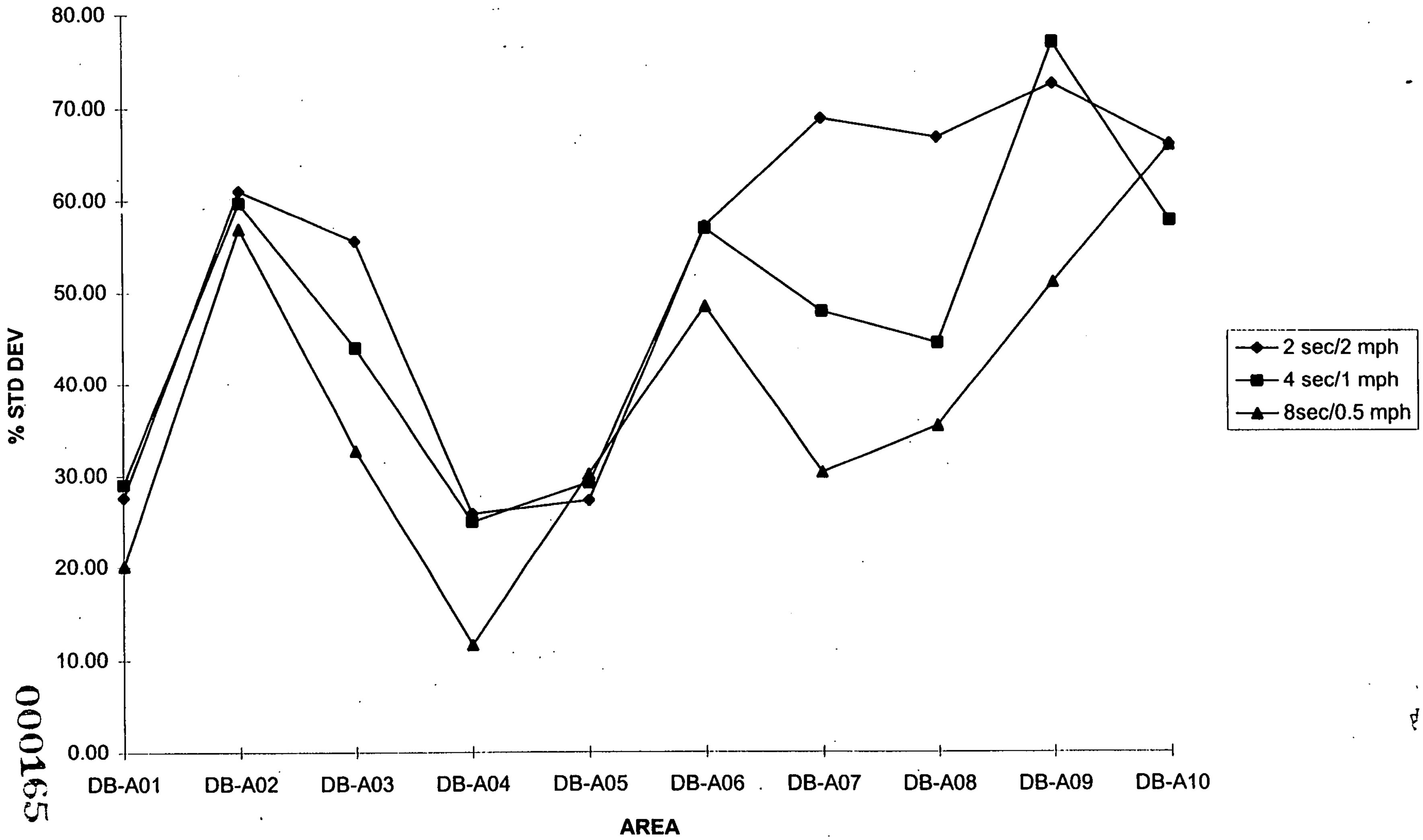


FIGURE B-10
THORIUM - 232 - USID AREA - MEAN

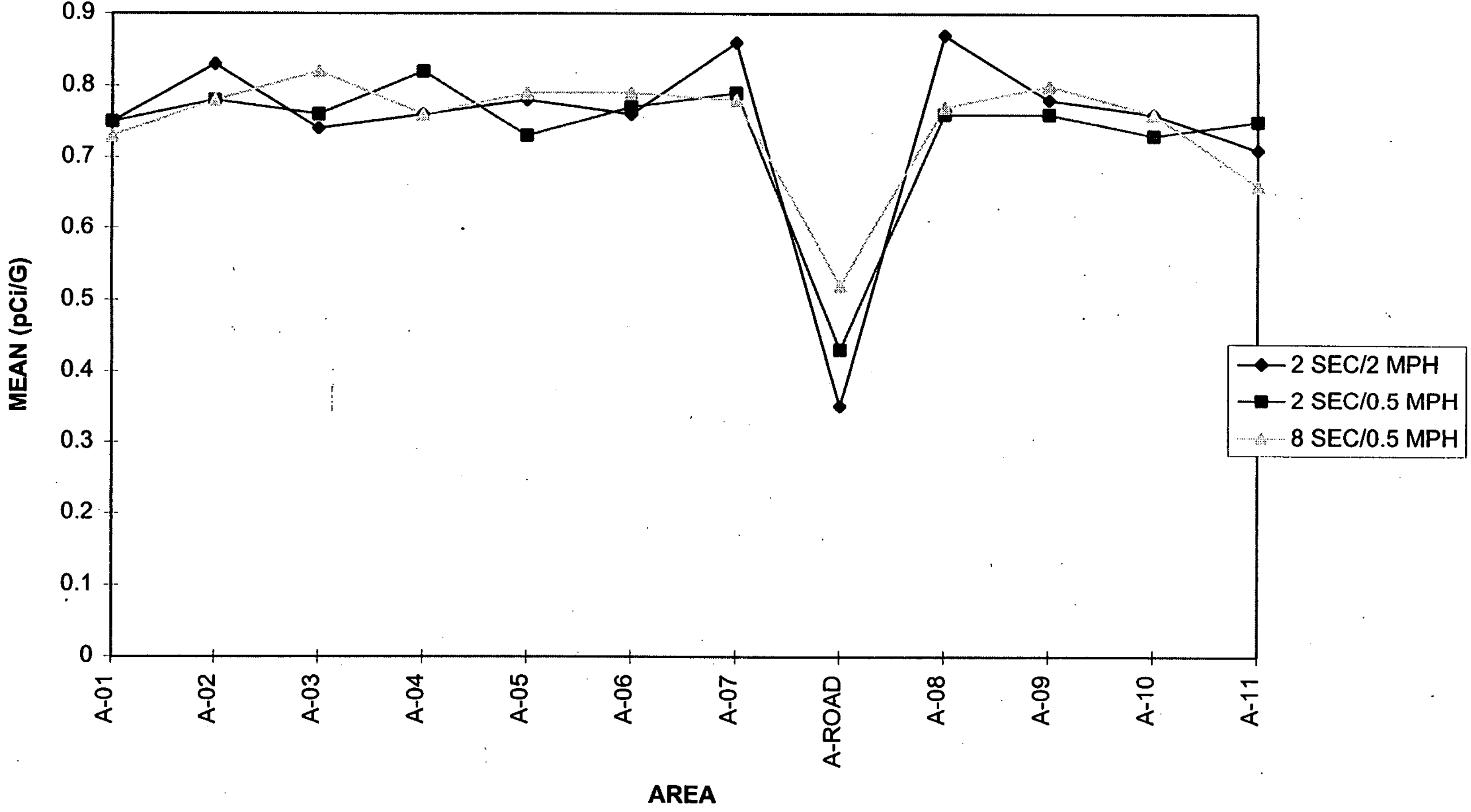


FIGURE B-11
THORIUM-232 - USID AREA - STANDARD DEVIATION

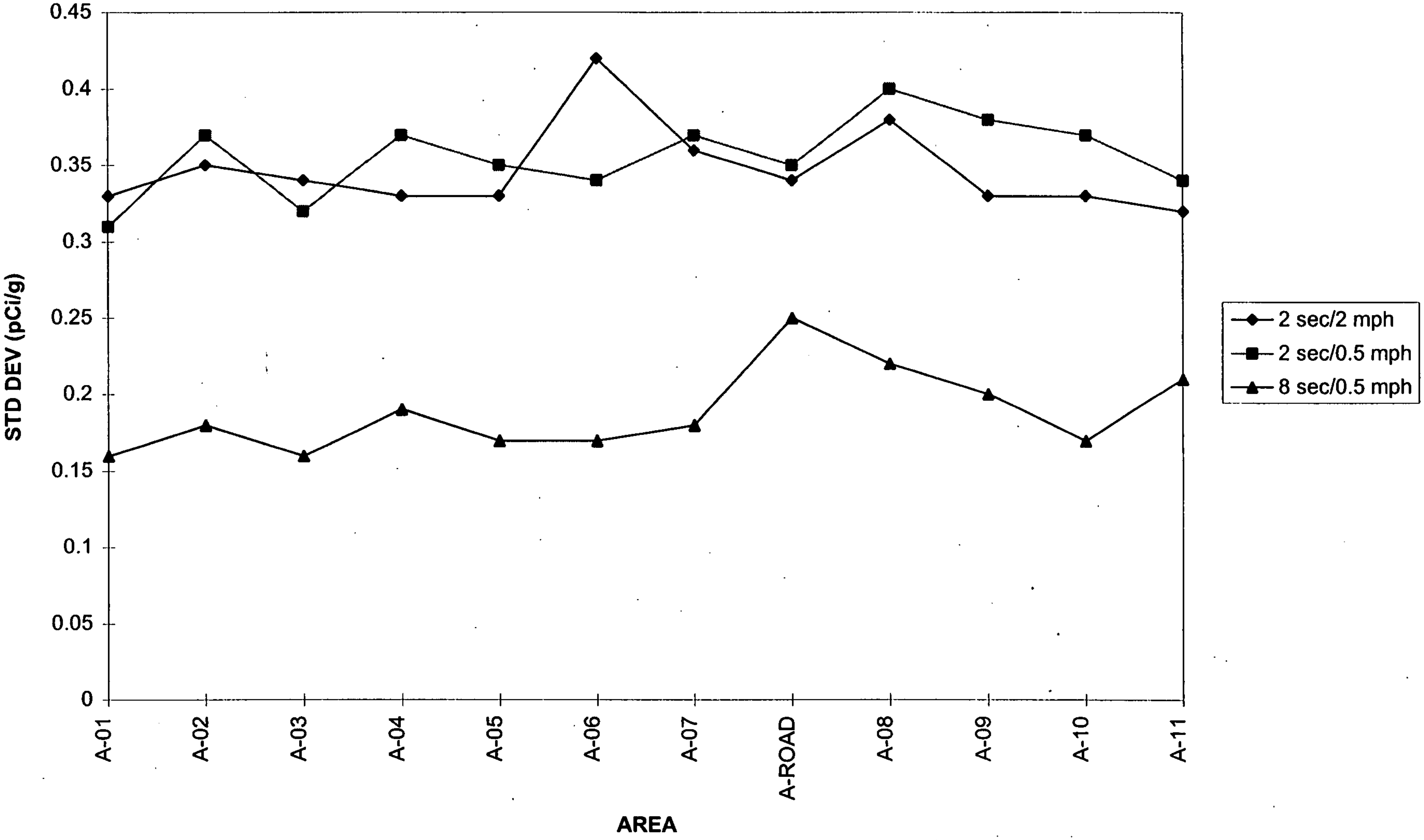


FIGURE B-12
THORIUM - 232 - USID AREA - % STANDARD DEVIATION

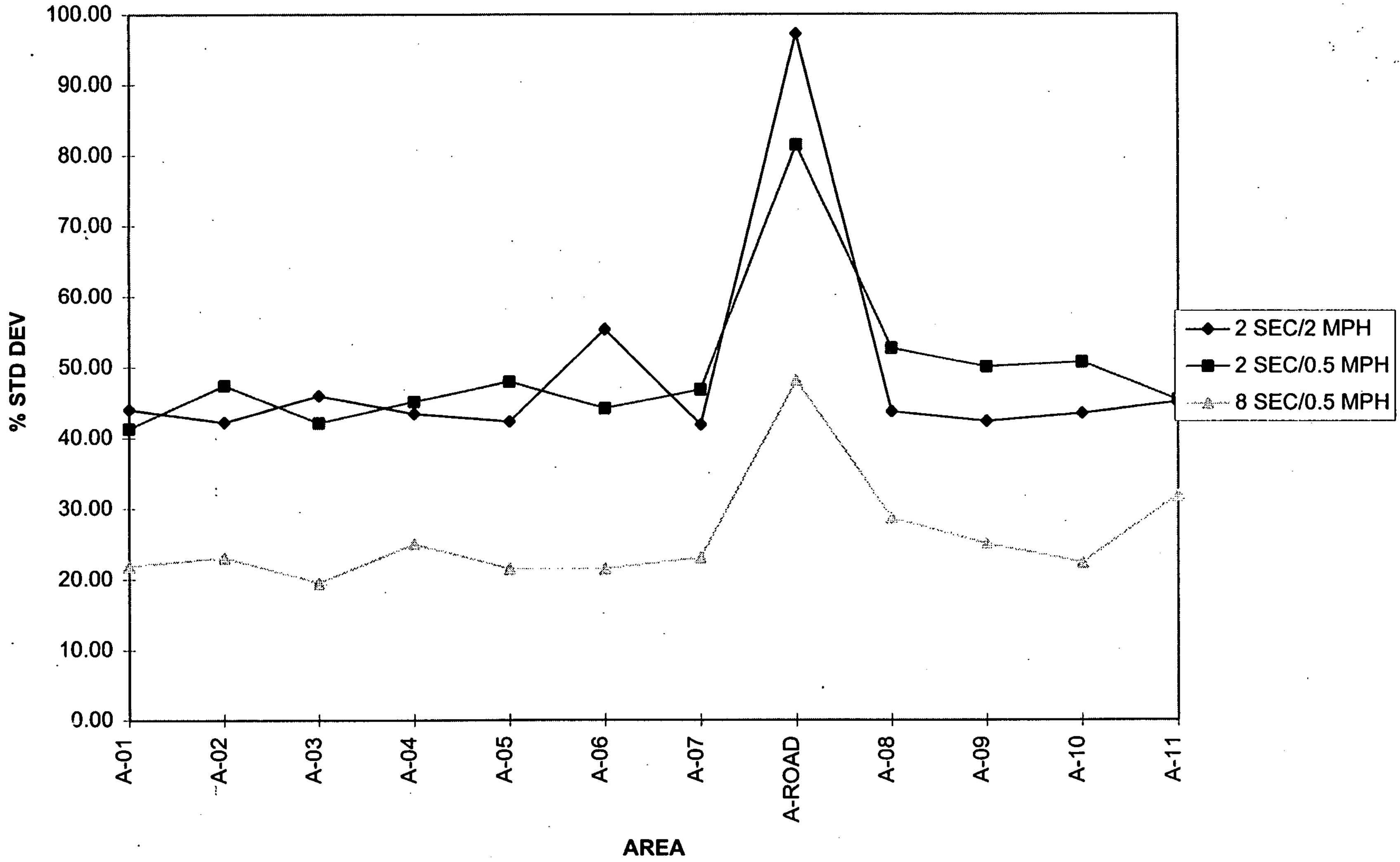


FIGURE B-13
THORIUM-232 - SOUTH FIELD - MEAN

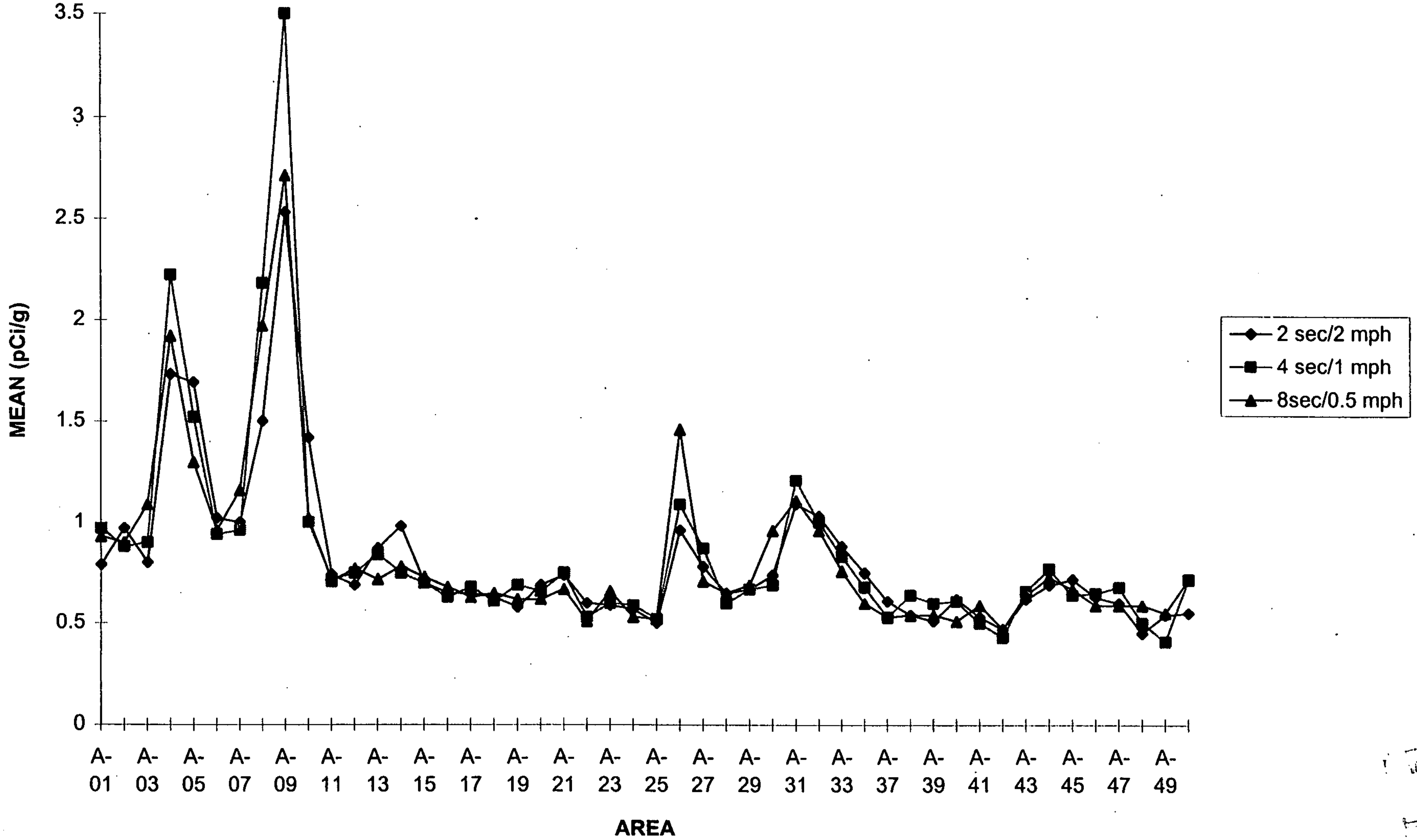


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FIGURE B-14

THORIUM-232 SOUTH FIELD - STANDARD DEVIATION

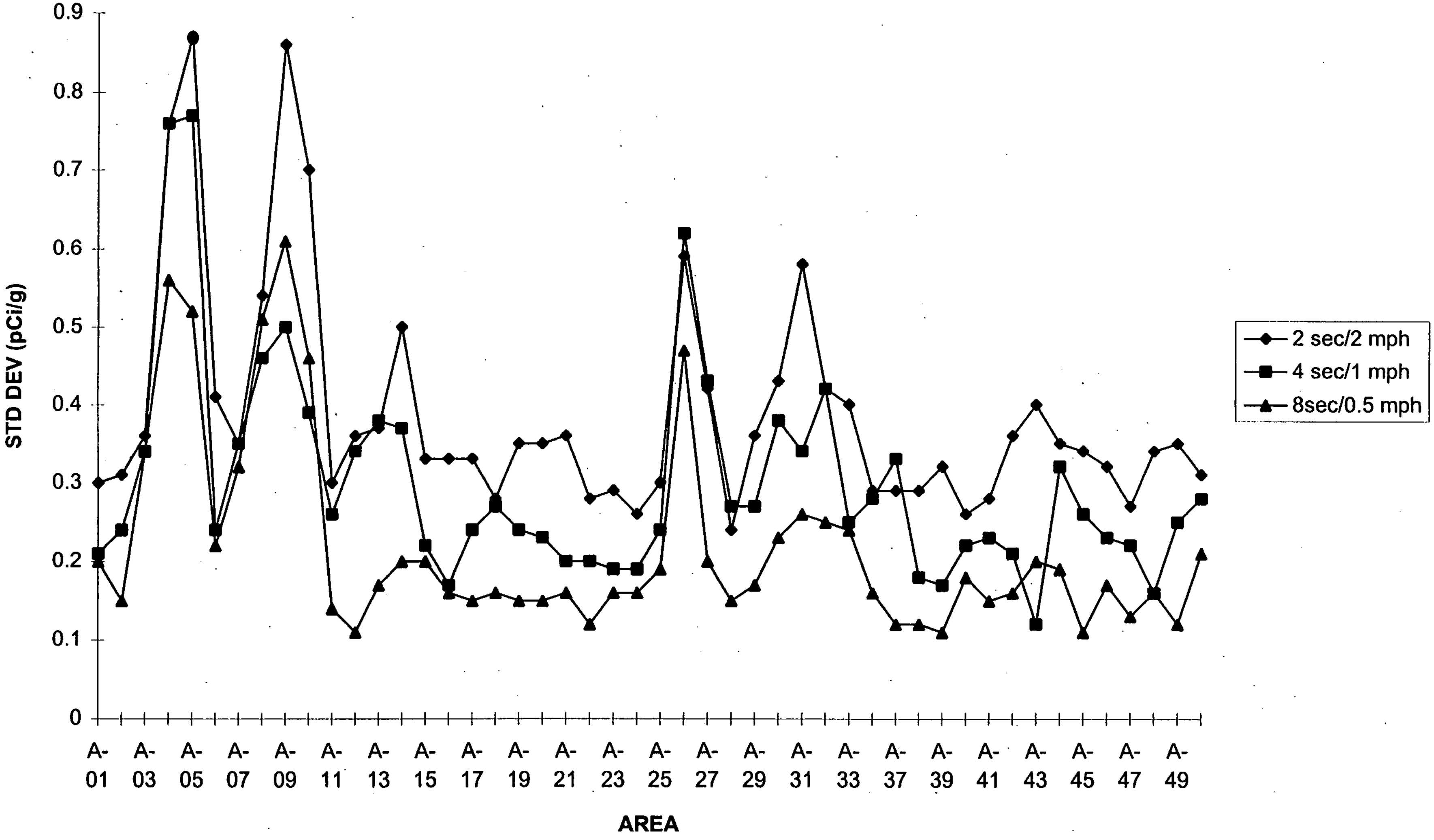

FIGURE B-15
THORIUM-232 - SOUTH FIELD - %STANDARD DEVIATION

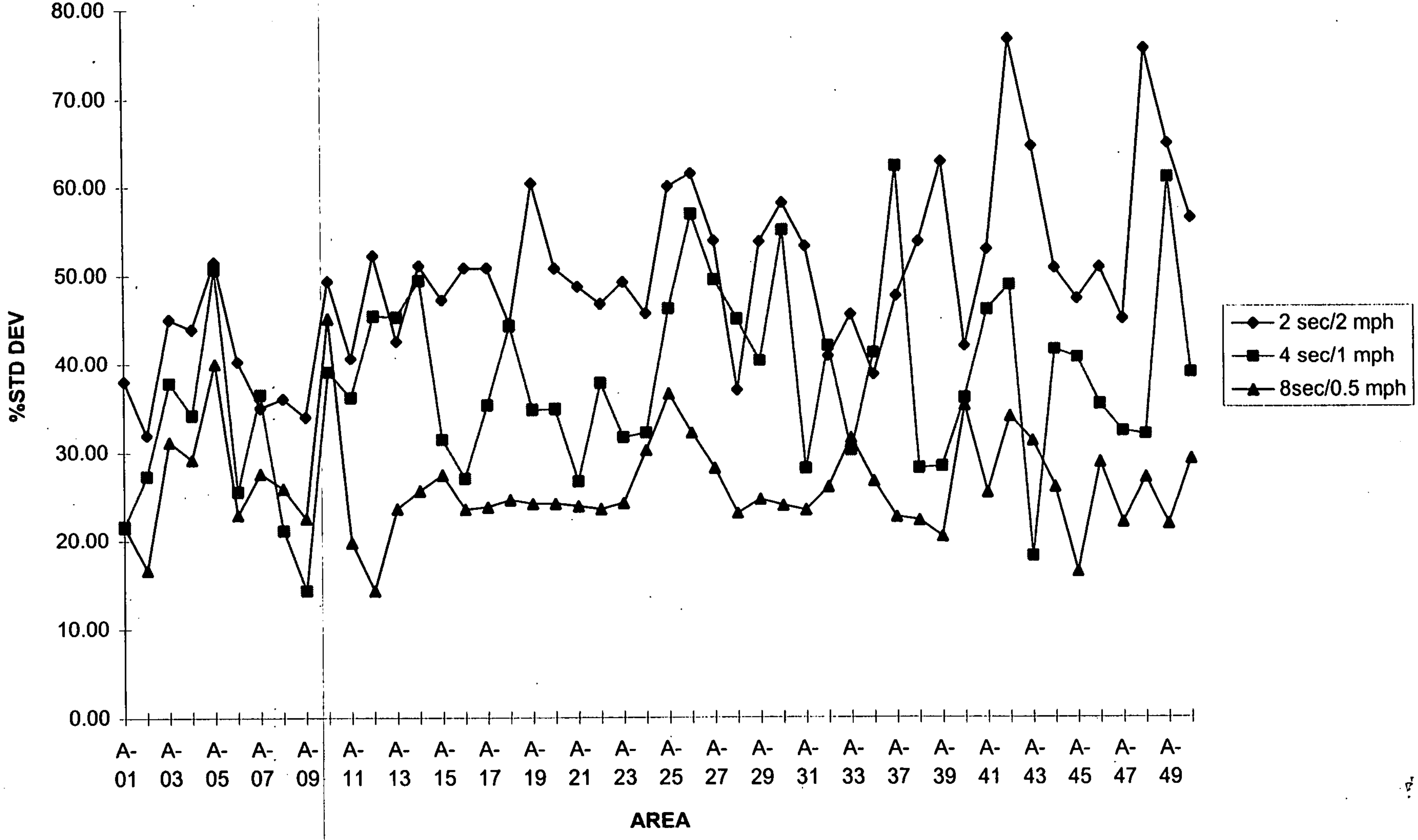

FIGURE B-16
THORIUM-232 DRUM BALING AREA - MEAN

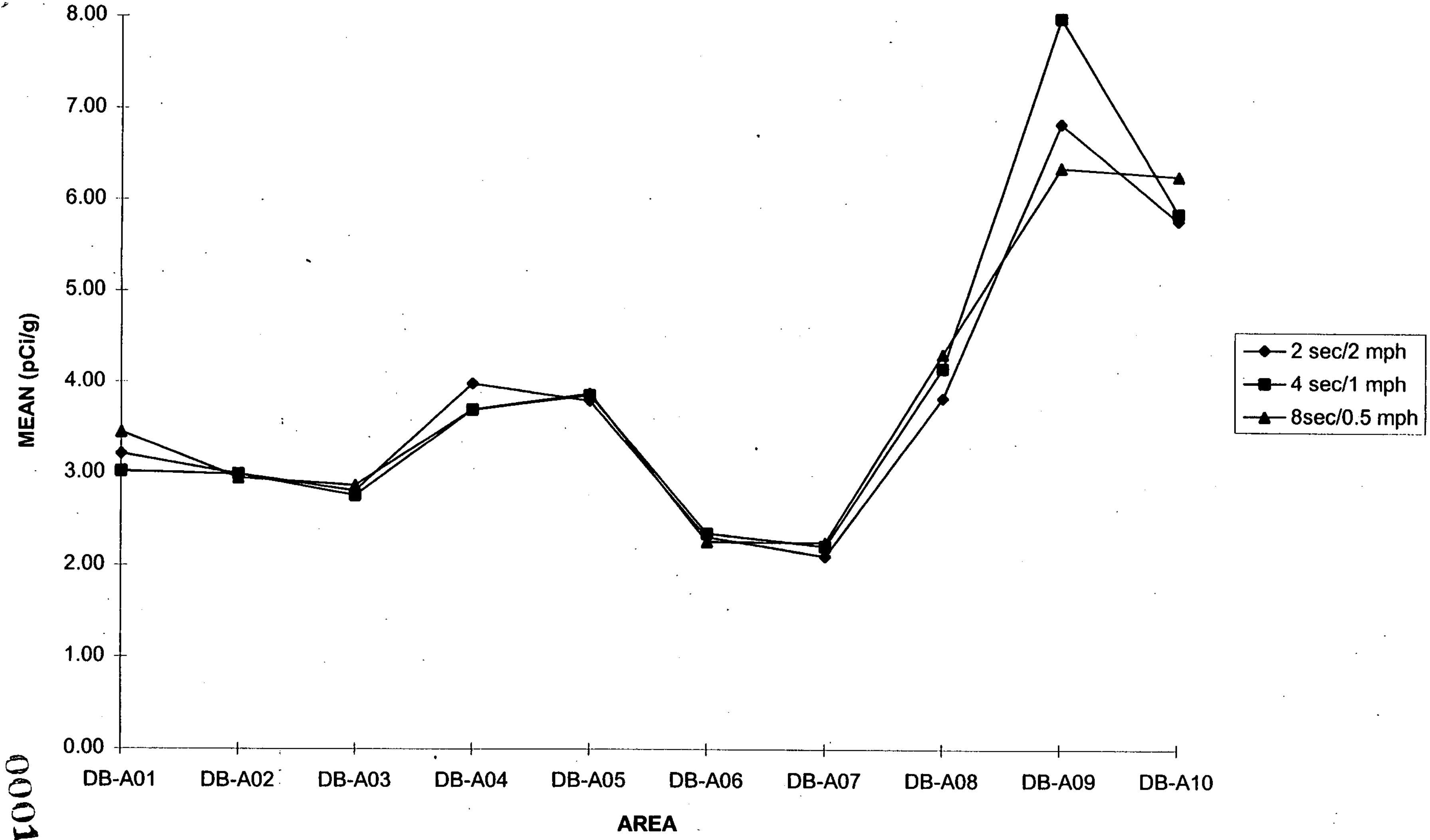

FIGURE B-17
THORIUM DRUM BALING AREA - STANDARD DEVIATION

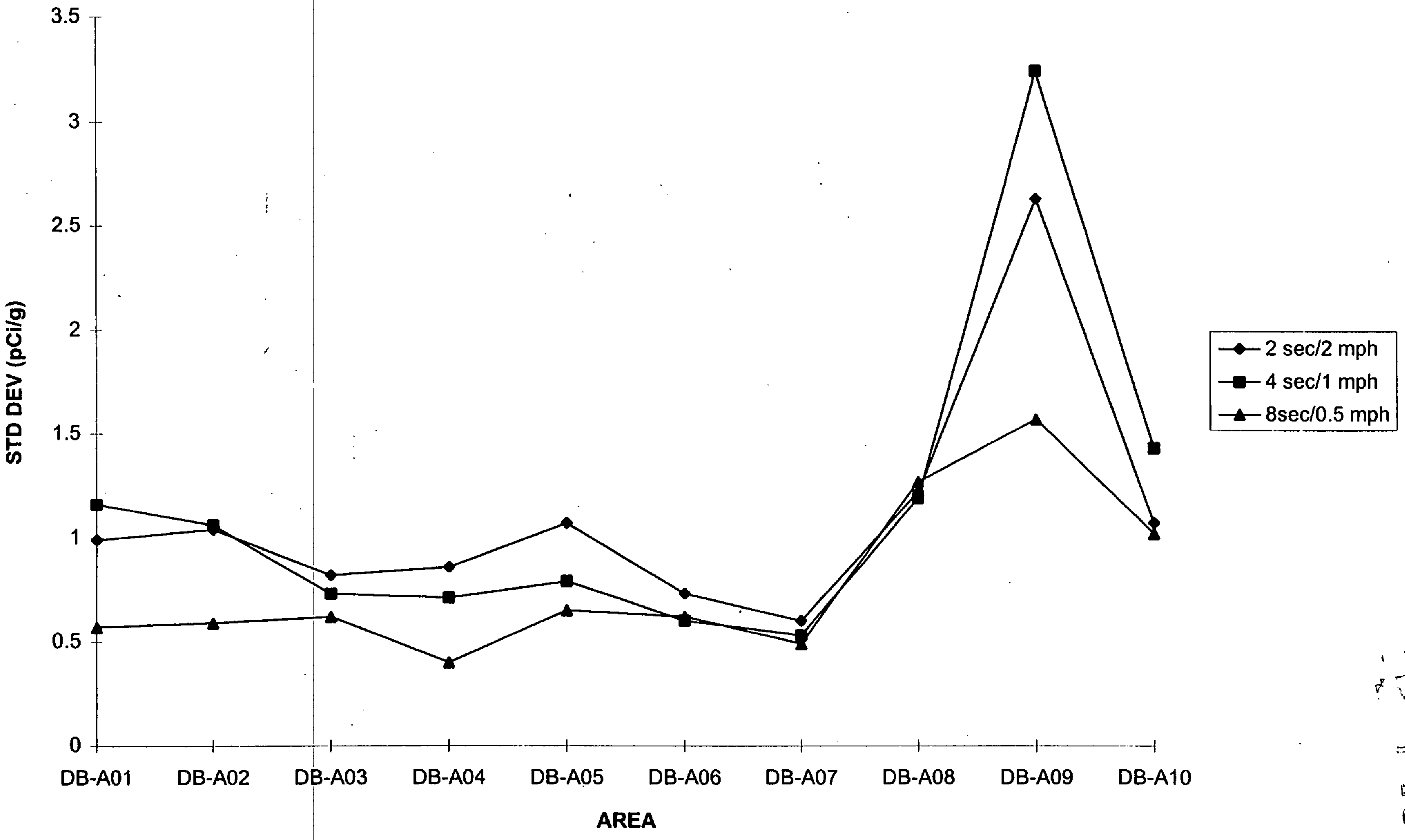

FIGURE B-18
THORIUM DRUM BALING AREA % STANDARD DEVIATION

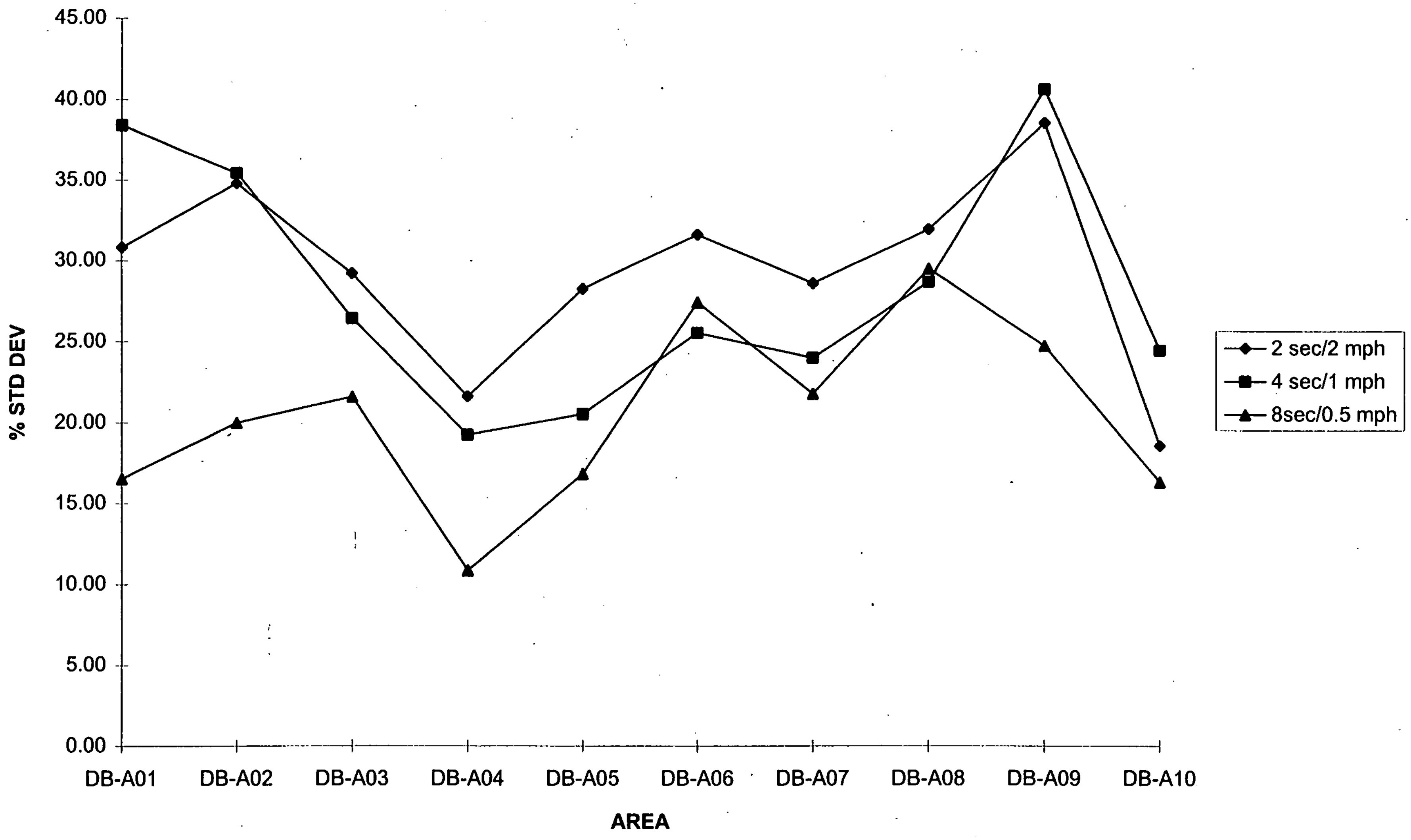

FIGURE B-19
RADIUM-226 - USID AREA - MEAN

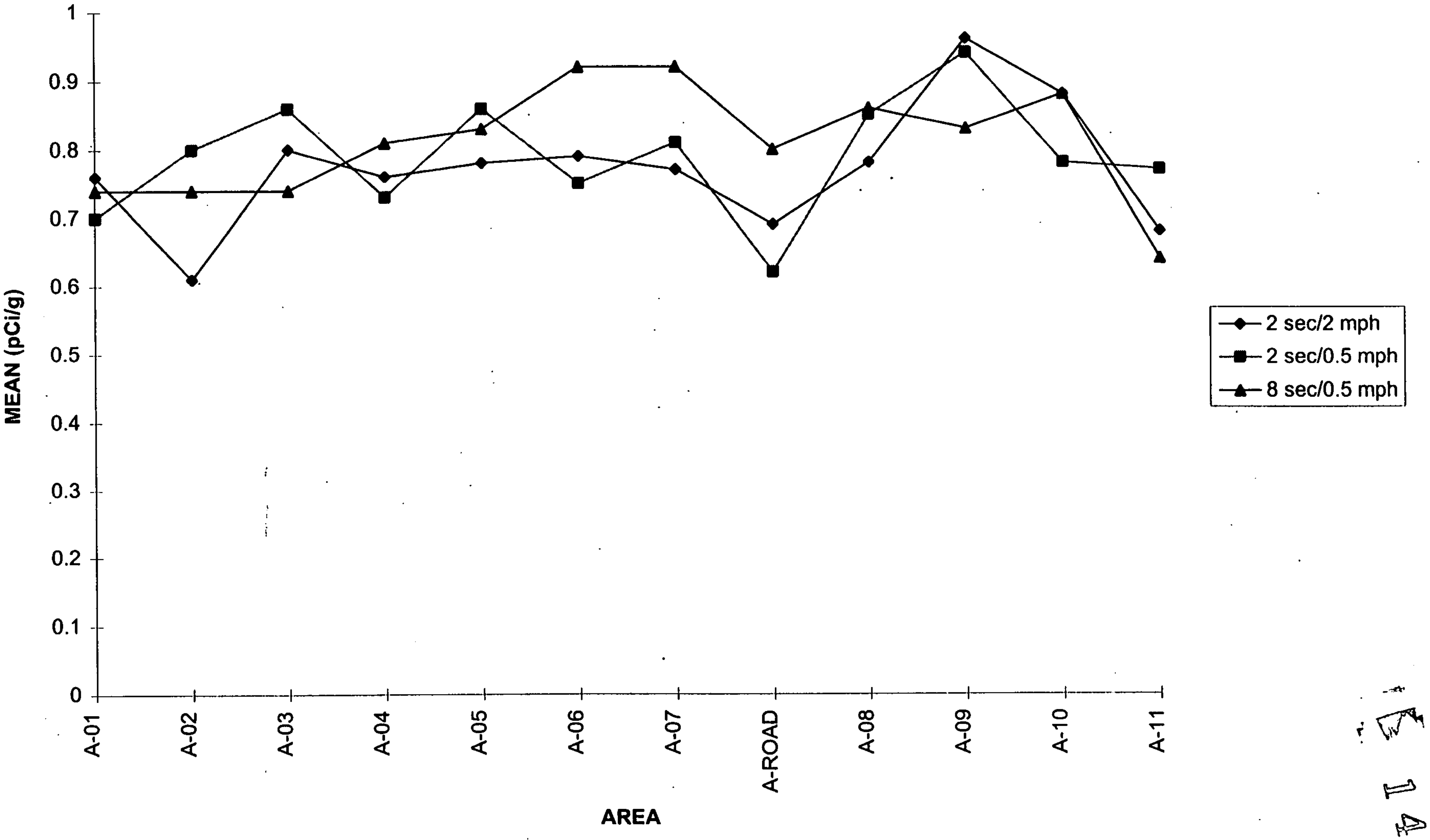

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FIGURE B-20
RADIUM-226 - USID AREA - STANDARD DEVIATION

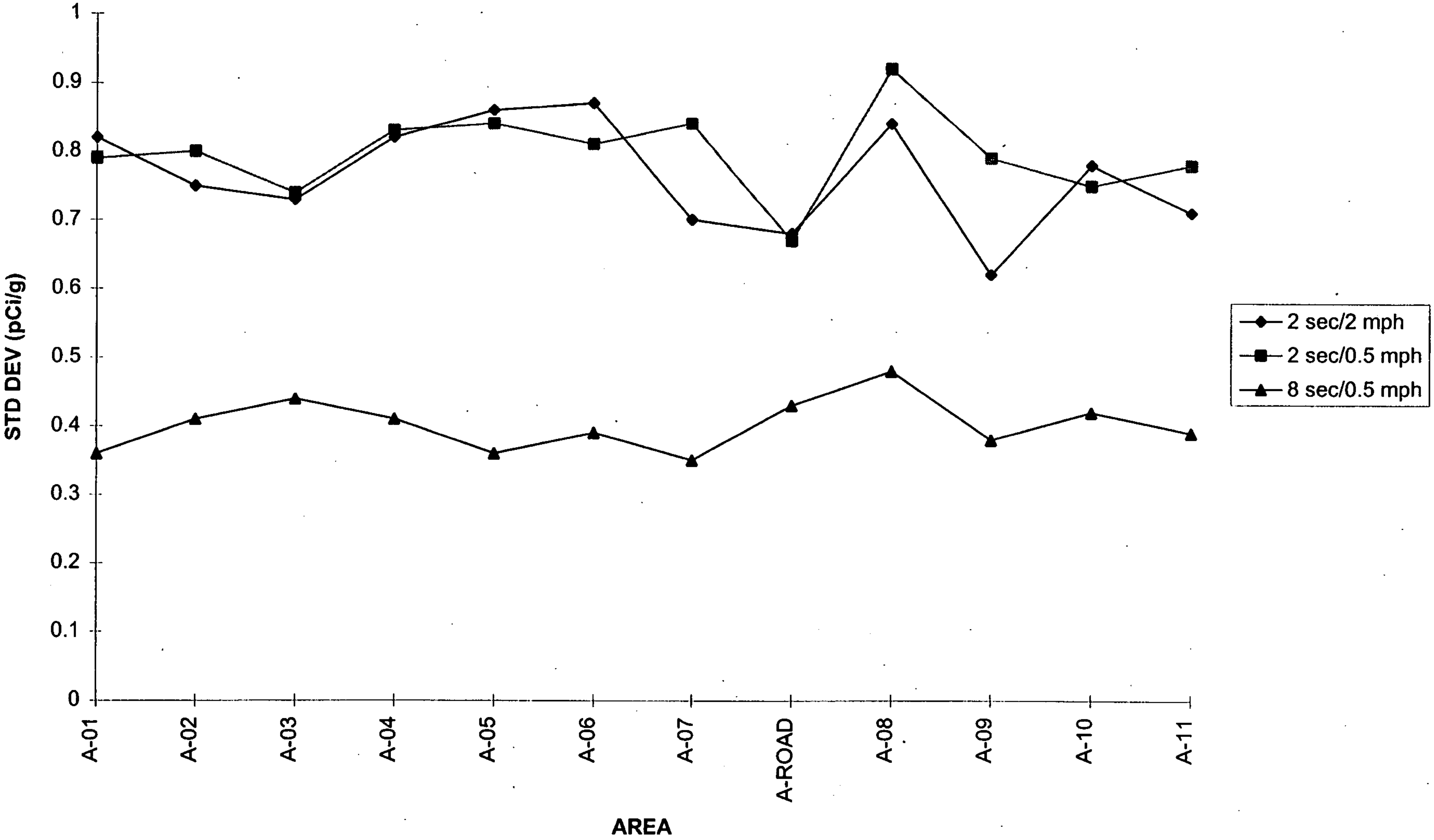


FIGURE B-21
RADIUM-226 - USID AREA - % STANDARD DEVIATION

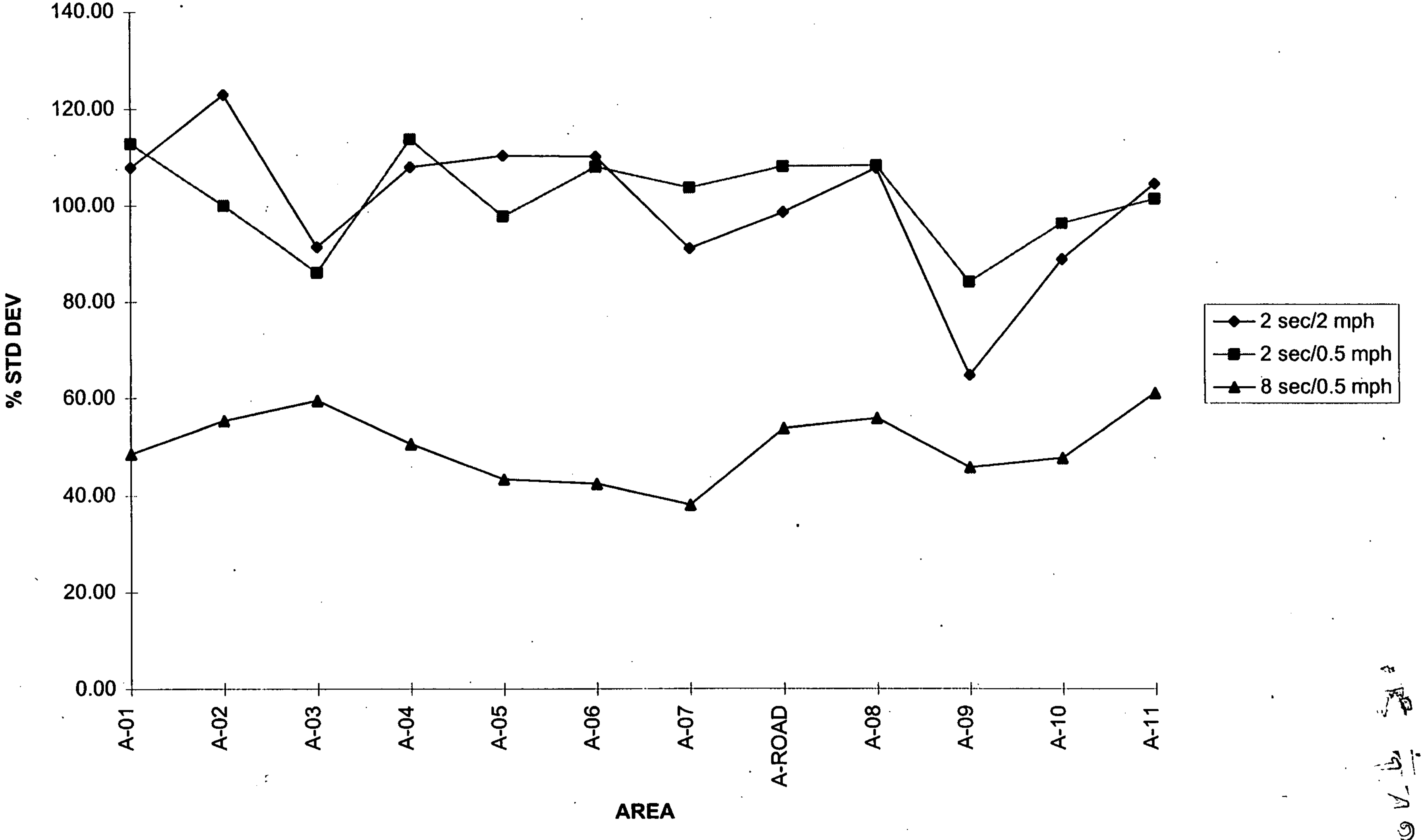


FIGURE B-22
RADIUM-226 - SOUTH FIELD - MEAN

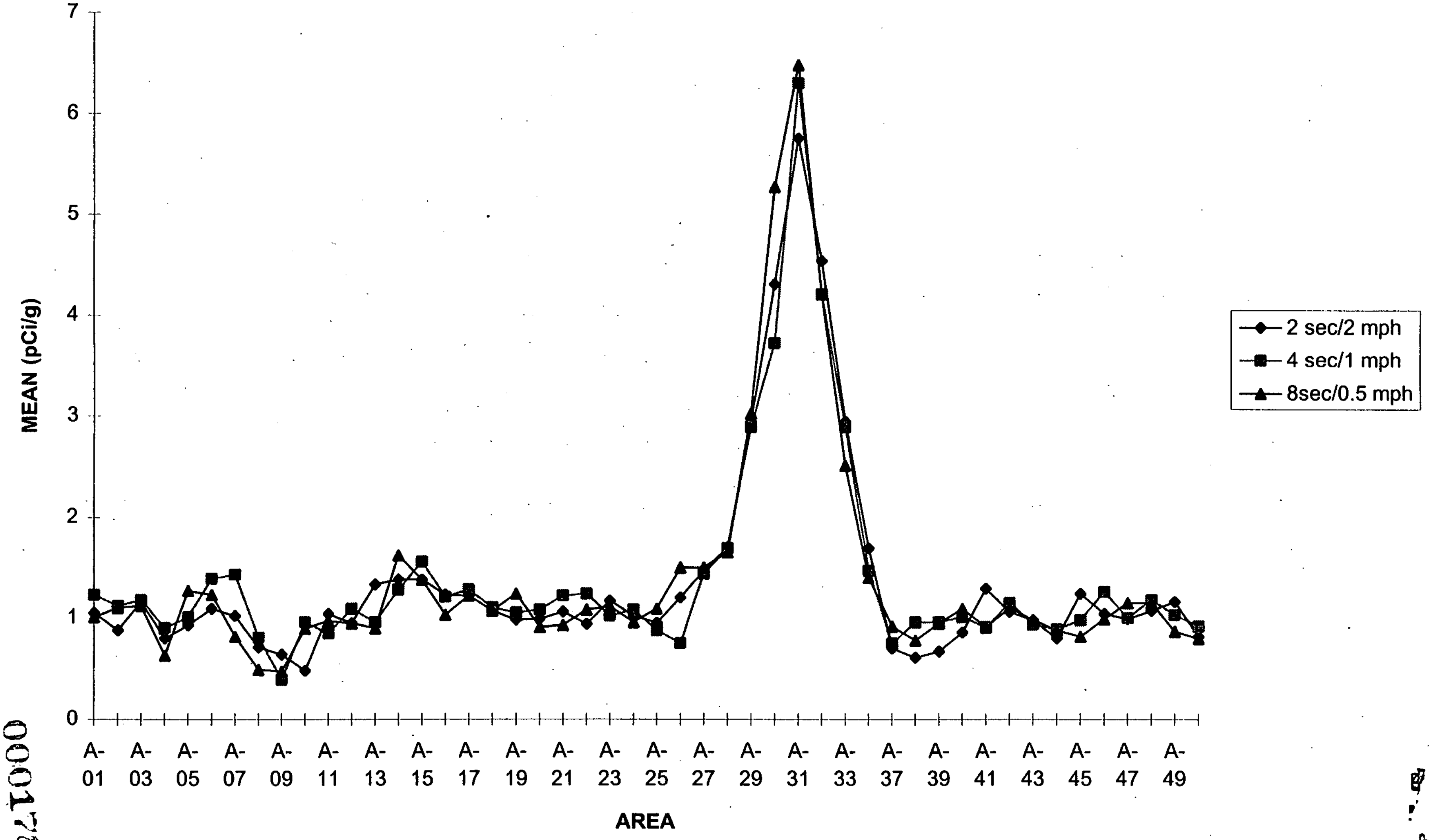


FIGURE B-23
RADIUM-226 SOUTH FIELD - STANDARD DEVIATION

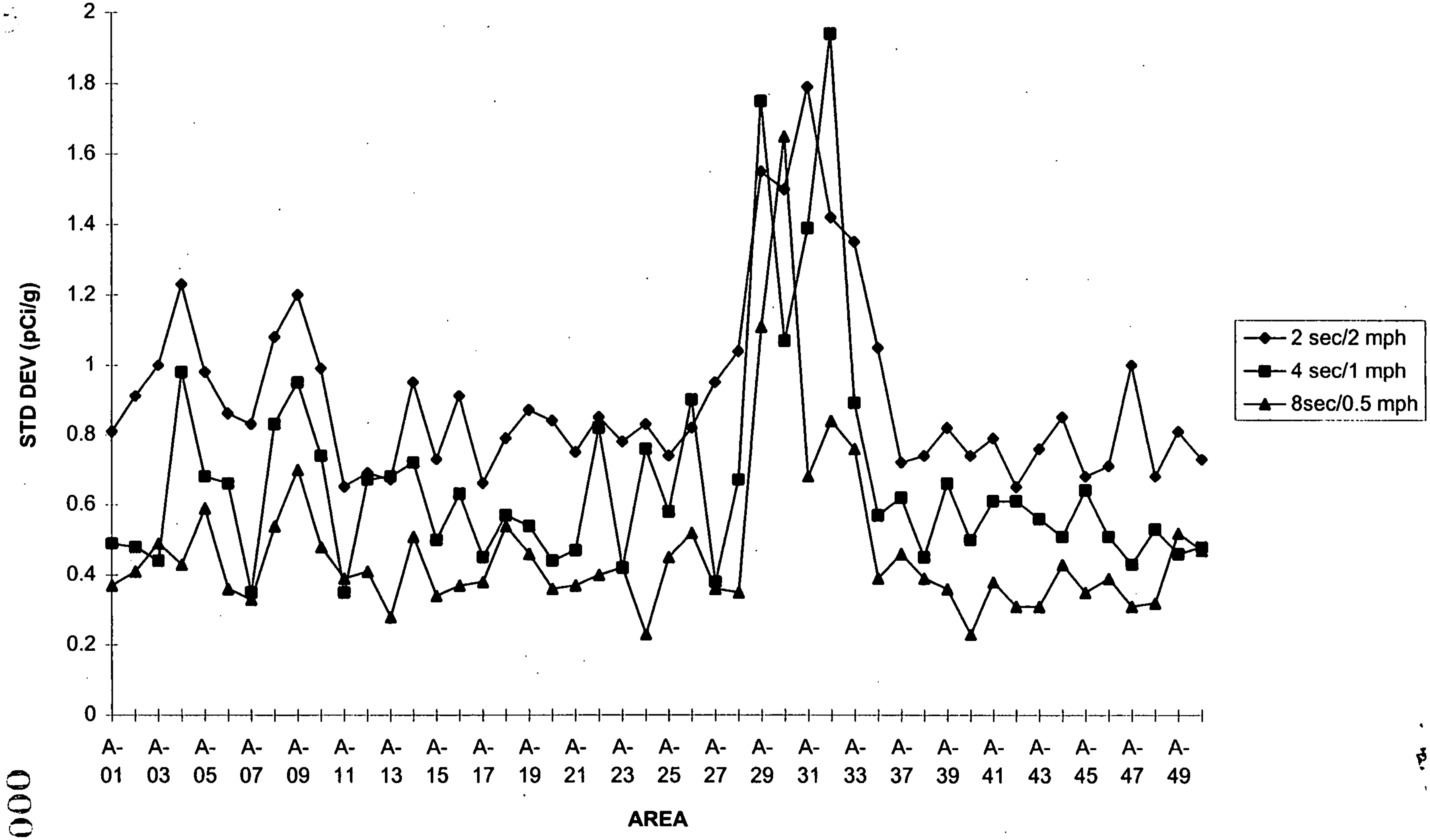


FIGURE B-24
RADIUM-226 - SOUTH FIELD - % STANDARD DEVIATION

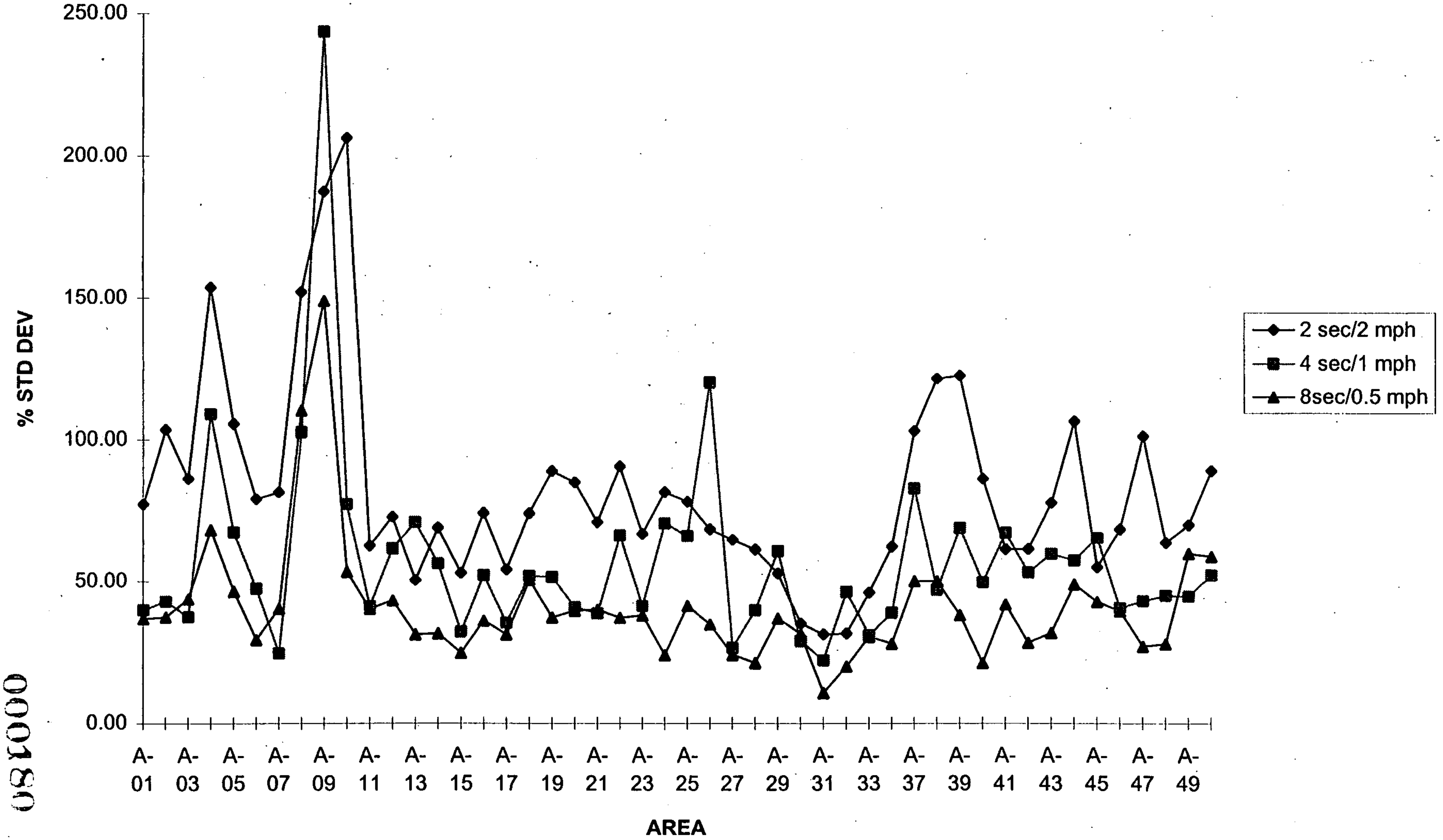


FIGURE B-25
RADIUM DRUM BALING AREA - MEAN

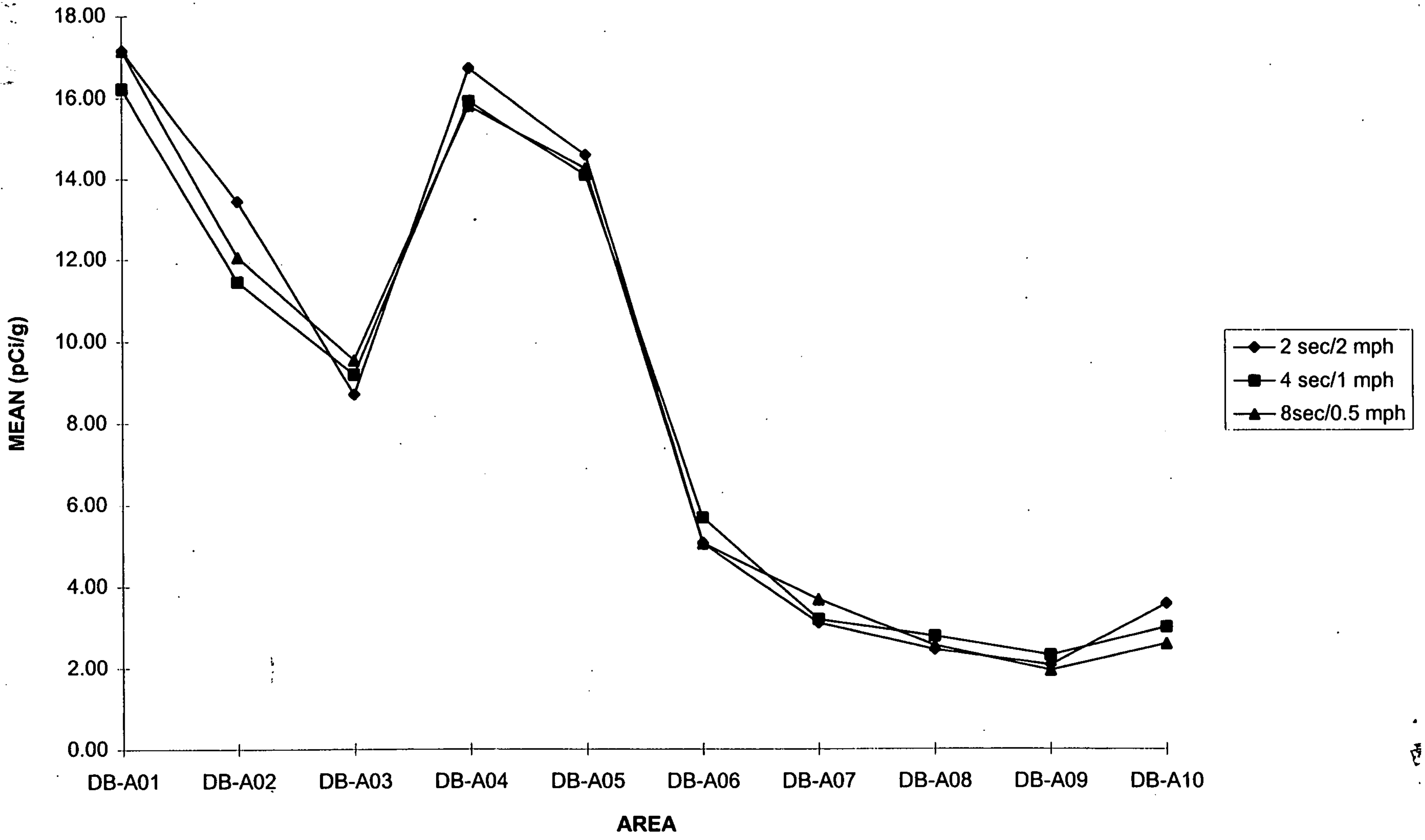


FIGURE B-26
RADIUM DRUM BALING AREA - STANDARD DEVIATION

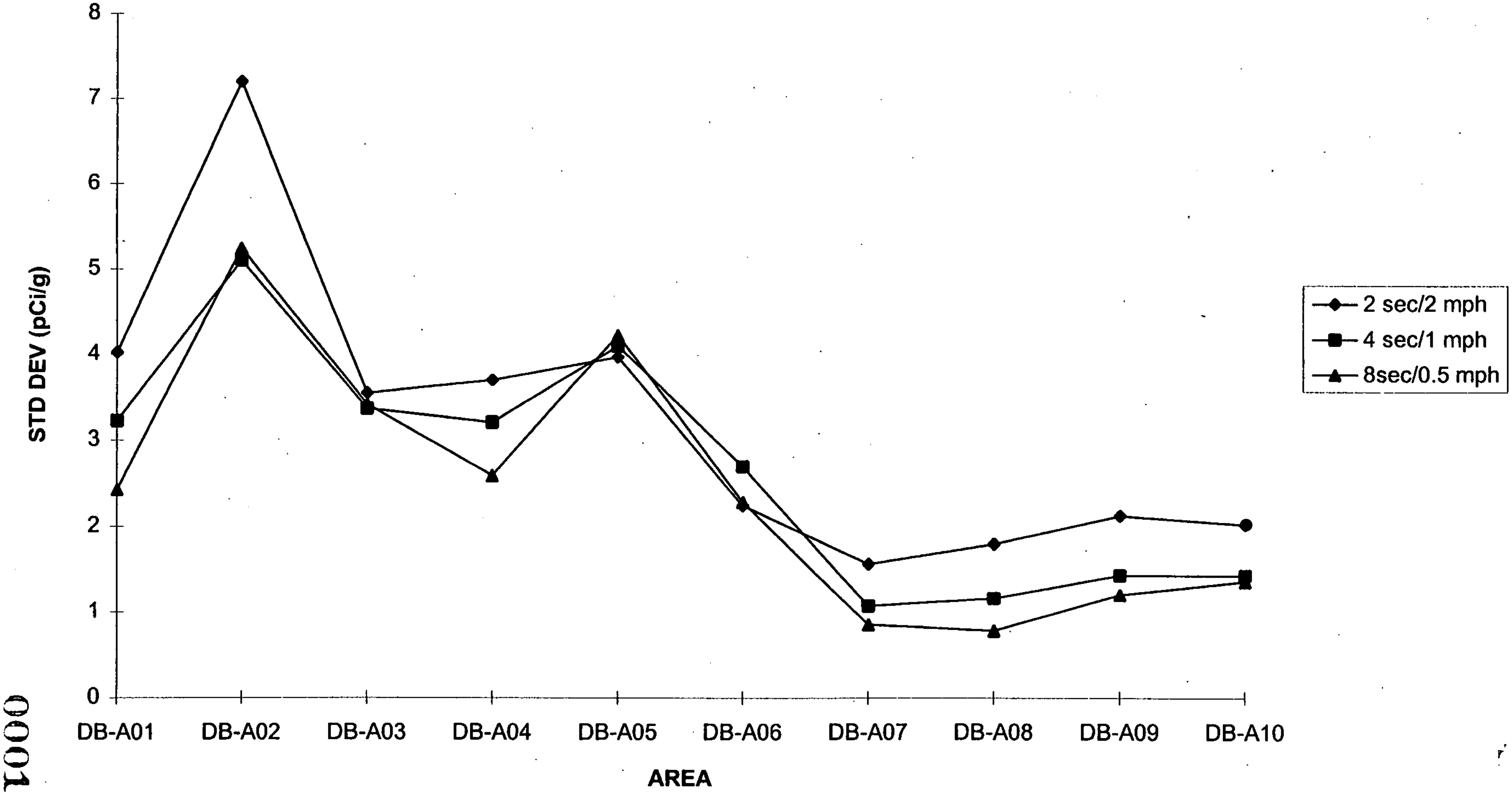


FIGURE B-27
RADIUM DRUM BALING AREA - % STANDARD DEVIATION

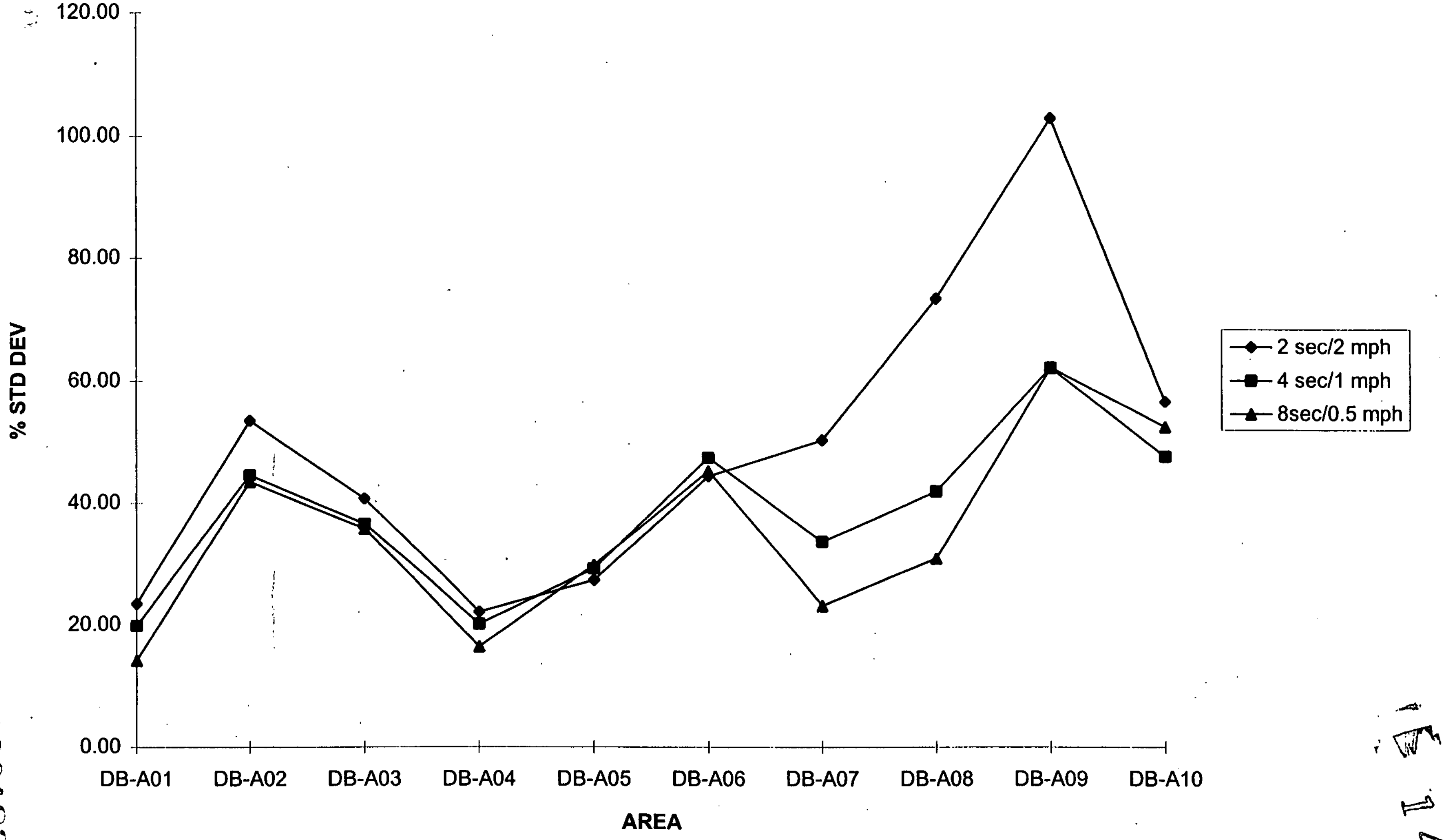


FIGURE B-28
GROSS CPS - USID AREA - MEAN

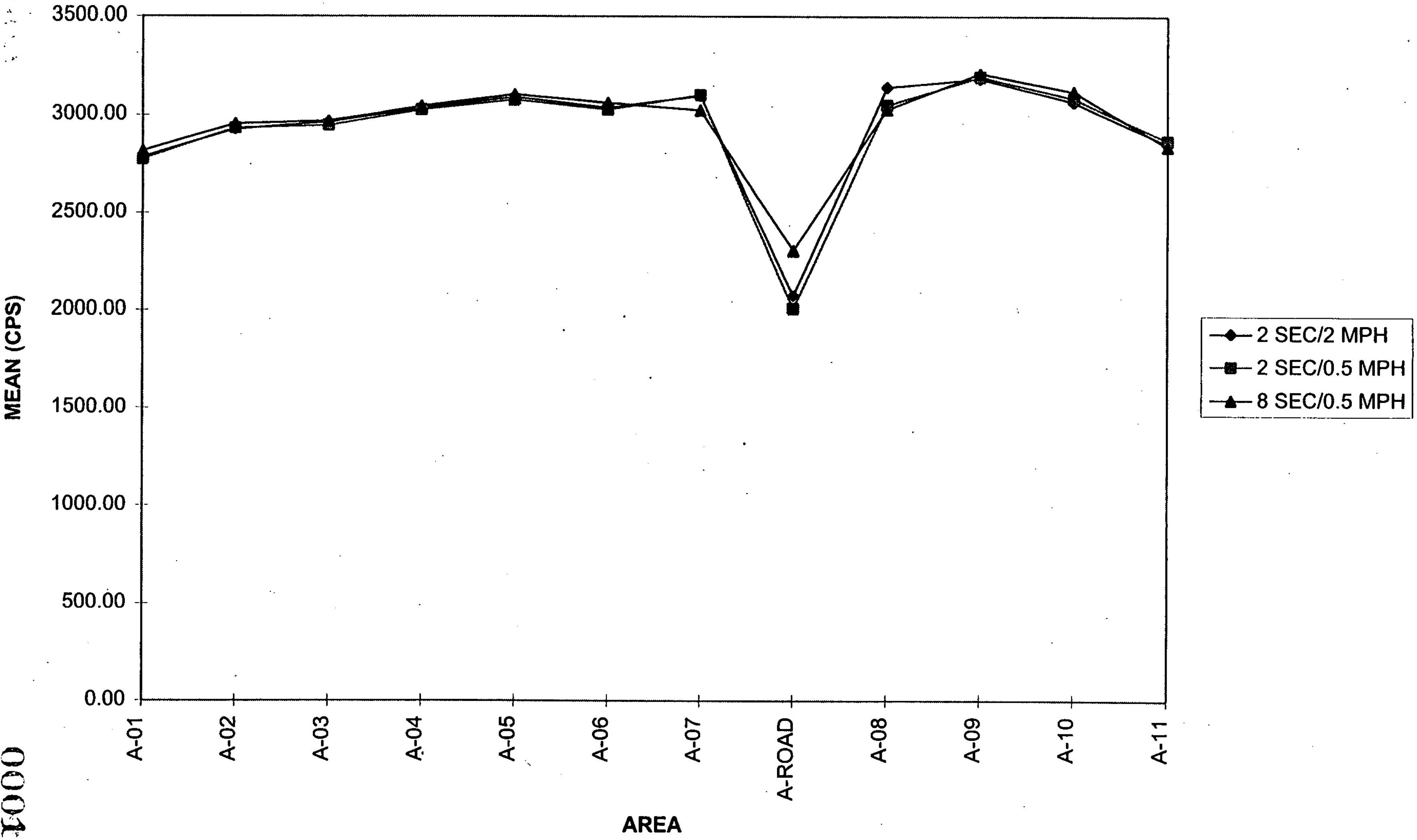


FIGURE B-29
GROSS CPS - USID AREA - STANDARD DEVIATION

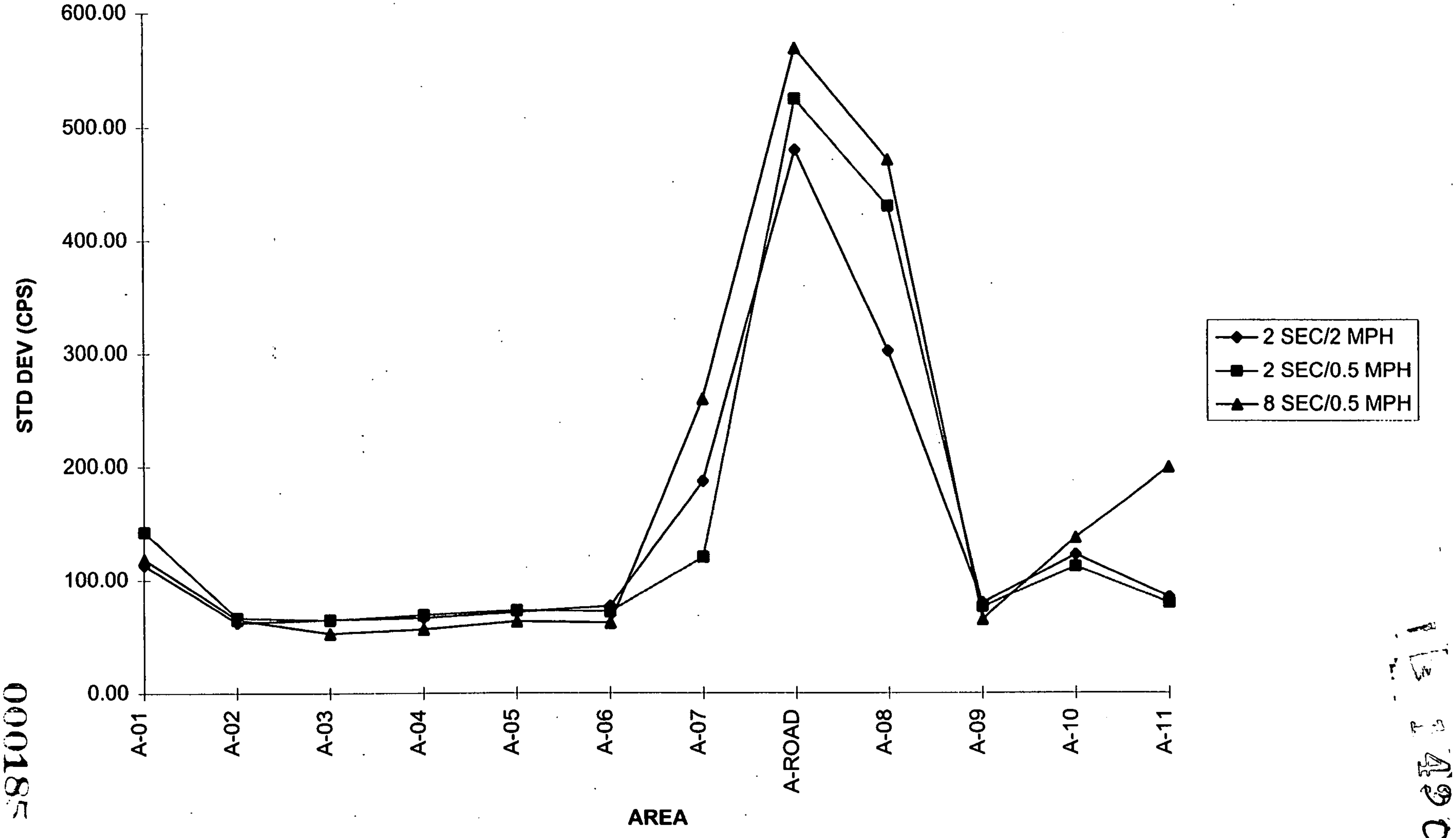


FIGURE B-30
GROSS CPS - USID AREA - % STANDARD DEVIATION

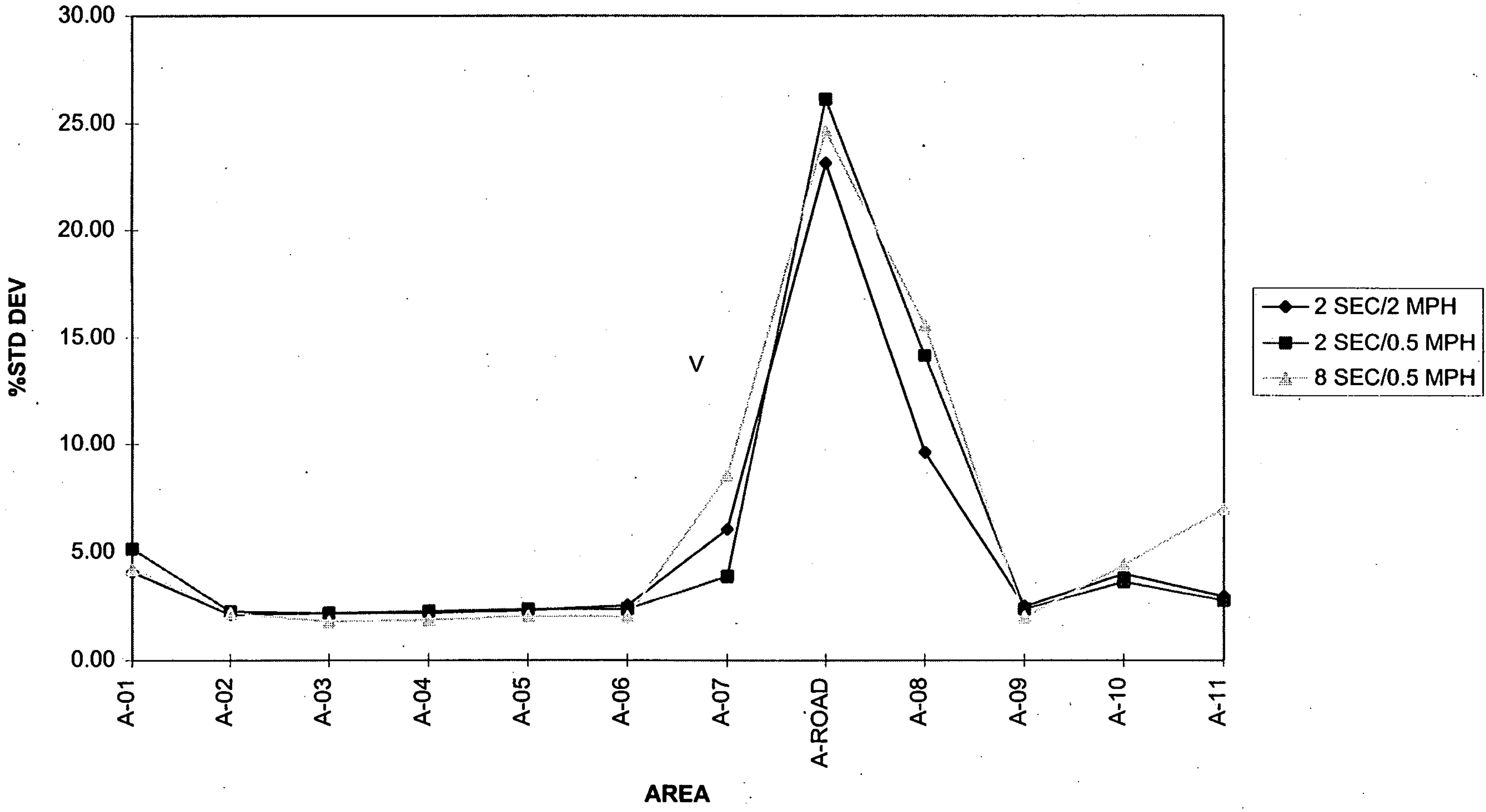


FIGURE B-31
GROSS CPS - SOUTH FIELD - MEAN

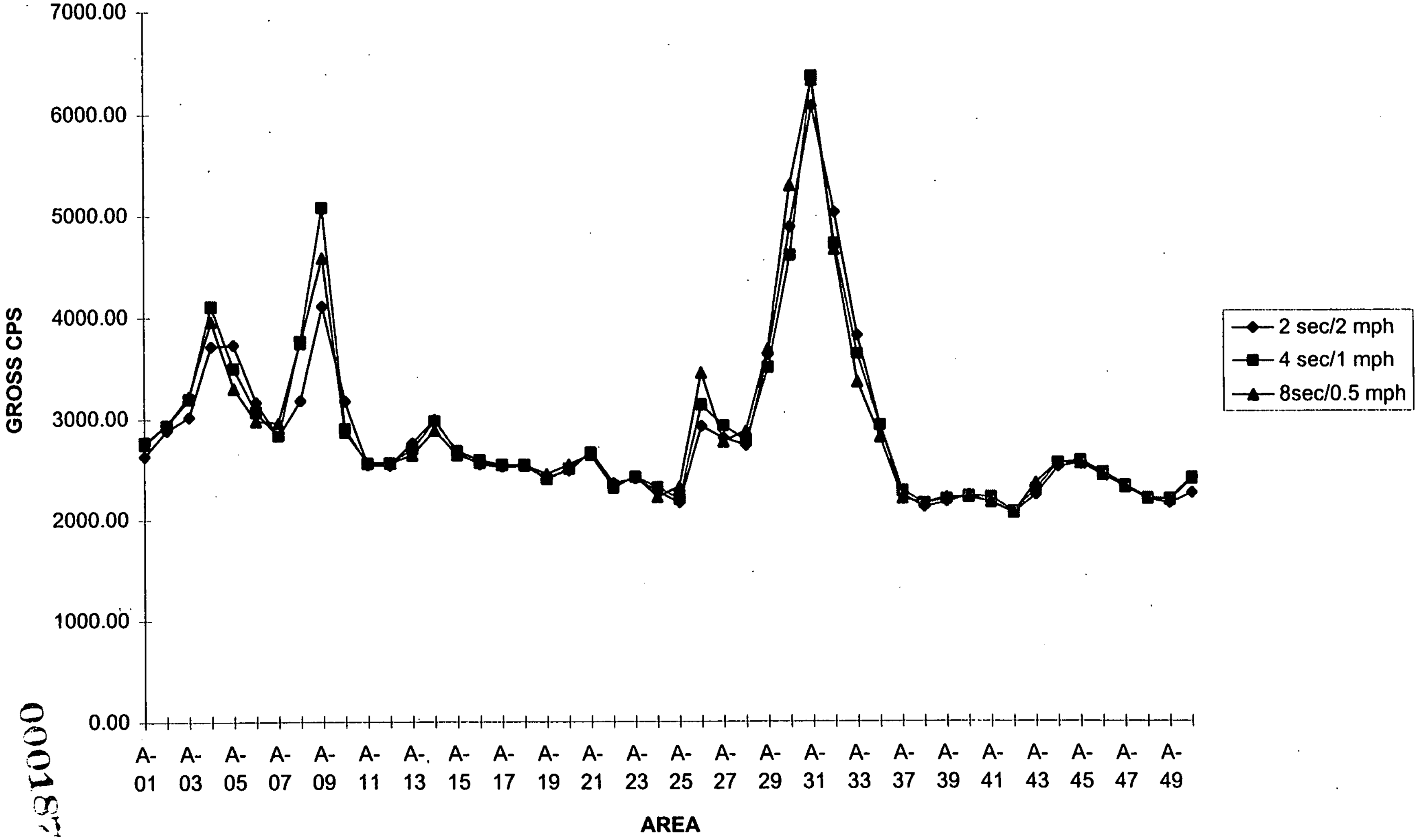
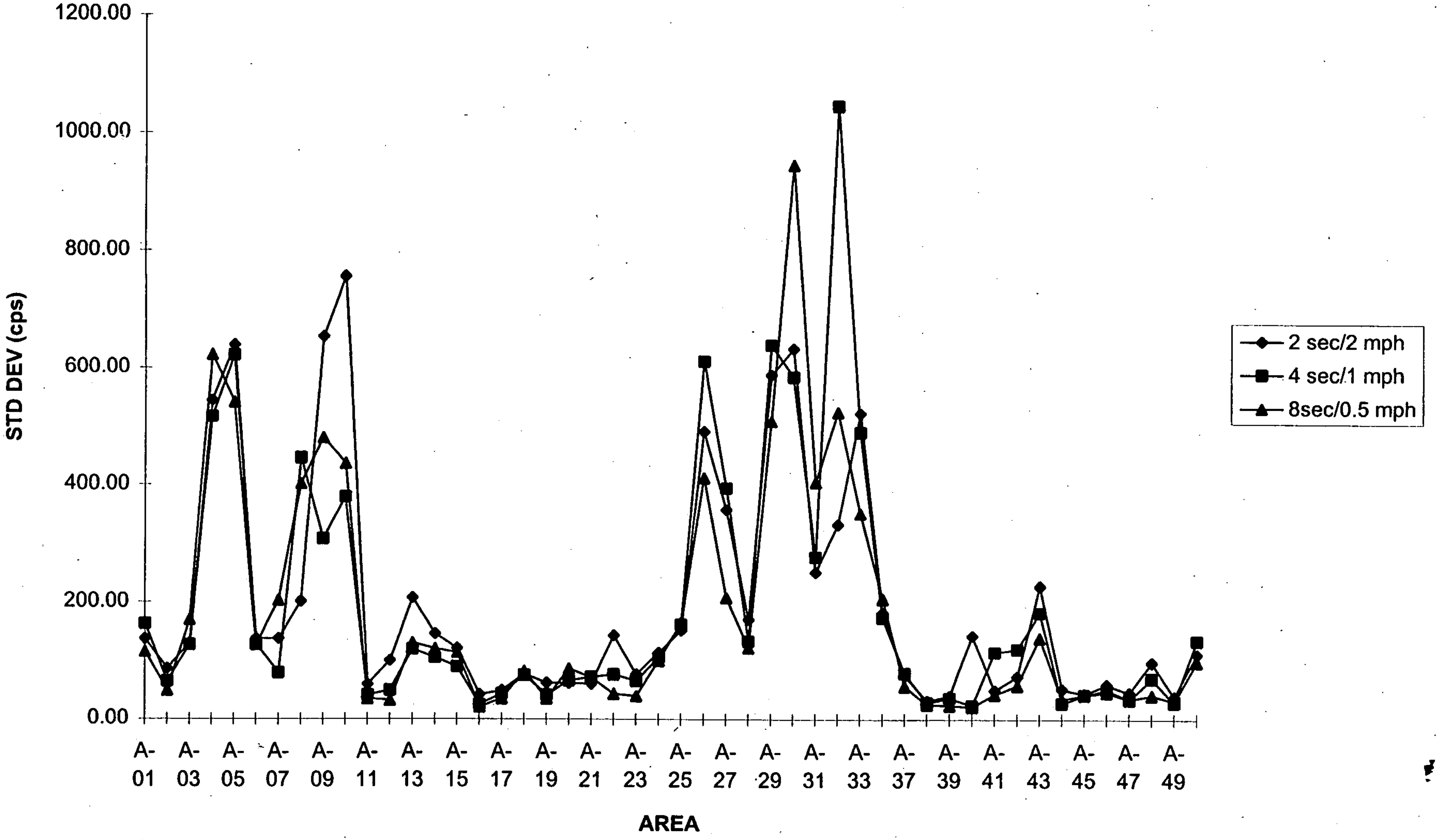
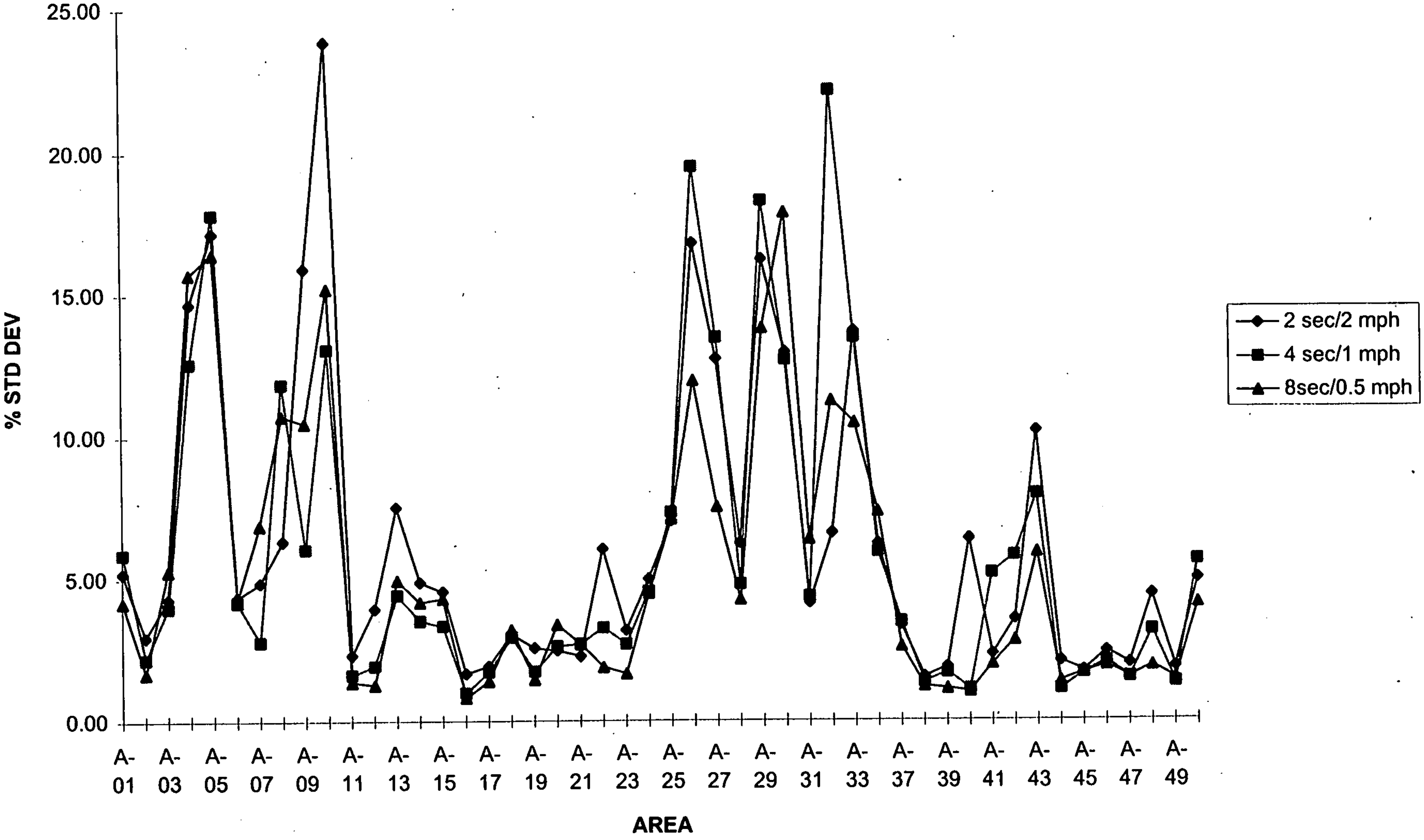


FIGURE B-32
GROSS CPS SOUTH FIELD - STANDARD DEVIATION



FIGURE B-33
GROSS CPS - SOUTH FIELD - %STANDARD DEVIATION